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NAVEODTECHCEN TECHNICAL REPORT TR-308

FINAL REPORT
REMOTE DETECTION OF UNEXPLODED ORDNANCE–GROUND PENETRATNG RADAR

FEBRUARY 1992

FINAL REPORT

Approved for public release; Distribution unlimited.

Prepared by
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THIS DOCUMENT DESCRIBES THE VEHICLE TOWED RANGE CLEARANCE GROUND PENETRATING RADAR SYSTEM DEVELOPED FOR THE ARMY CORPS OF ENGINEERS. A DEMONSTRATION SYSTEM WAS BUILT AND TESTED. SYSTEM CAPABILITIES ARE DETAILED AND RECOMMENDED UPGRADES ARE LISTED. SYSTEM OPERATION IS DESCRIBED AND TEST RESULTS ARE INCLUDED.

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FINAL TECHNICAL REPORT
REMOTE DETECTION OF UNEXPLODED ORDNANCE - GROUND PENETRATING RADAR

TASK 9

PREPARED FOR

NAVAL RESEARCH LABORATORY
4555 OVERLOOK AVENUE, SW
WASHINGTON, DC 20375-5000

UNDER CONTRACT NO. N00014-86-C-2266
RESEARCH OF NOVEL CHEMICAL & OPTICAL
DIAGNOSTIC TECHNIQUES

PREPARED BY

GEO-CENTERS, INC.
7 WELLS AVENUE
NEWTON CENTRE, MASSACHUSETTS 02159

FEBRUARY 1991

GEO-CENTERS, INC.

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ACRONYMS

ACE	Army Corps of Engineers
CMU	Control Measurement Unit
GPR	Ground Penetrating Radar
LID	Local Intensity Detector
MT/R	Master Transmitter/Receiver
NAVEODTECHCEN	Naval Explosive Ordnance Disposal Technology Center
NRL	Naval Research Laboratory
OCDC	Operator Control & Display Computer
PCI	Power Curve Imaging
RC	Radar Controller
RCC	Radar Command Center
RNS	Remote Navigation Station
RTP	Radar Tow Platform
RTV	Radar Tow Vehicle
TGU	Track Guidance Unit
T/R	Transmitter/Receiver

Executive Summary

The US Congress, through Public law 98-212, charged the Department of Defense to institute a remedial action program to clear ranges and areas contaminated with hazardous explosive materials and ordnance. As part of the response, the US Army Corps of Engineers tasked the US Navy, as the lead service in Explosive Ordnance Disposal (EOD), to develop and demonstrate different systems each capable of detecting, locating, and partially identifying shallow buried, unexploded ordnance. The Naval Explosive Ordnance Disposal Technology Center (NAVEODTECHCEN), through the Naval Research Laboratory (NRL) and various contractors, reviewed current technology and identified three technological approaches offering high promise of success on a responsive time scale: 1) surface electromagnetics, 2) surface magnetometry, and 3) borehole electromagnetics/magnetometry. A demonstration prototype Ground Penetrating Radar (GPR) Ordnance Search System (RADAR), based on surface electromagnetics, was developed and delivered to the NAVEODTECHCEN under Contract Number N00014-86-C-2266.

The traditional method of GPR field operations involves translating a single GPR transmitter-receiver antenna configuration along a survey line by hand. The resulting analog signal is directed to a magnetic tape recorder or an electrostatic plotter for display and interpretation by visual inspection. Survey speeds must be kept slow to minimize uneven trace spacings which distort the subsurface image. Unprocessed GPR data is further complicated by signal ringing and reverberation, reflection from geologic structures, and noise. Evaluation of the data through visual inspection therefore requires a skilled interpreter which is both time consuming and expensive. In order to reduce expense, survey line spacing is typically large thereby limiting the survey resolution. Further, visual inspection of the data is subject to non-uniform interpretation and operator bias.

RADAR is an automated, multisensor, off-road, ordnance search system, whose mission objectives are to:

- Conduct surveys of contaminated areas at a nominal rate of twenty acres per day
- Detect and locate buried ordnance with an accuracy of ± 1 meter (3.2 feet) to a nominal depth of 4.5 meters (15 feet)
- Generate hard copy site and target maps

It is a tailored array of commercially-available electromagnetic GPR antennas towed by a four wheel drive vehicle. Data is acquired using a computer driven search system. Accurate antenna position is achieved through a microwave navigation system which also provides operator heading information, eliminating the need for manually erected track lines. Both location information and GPR data are digitally recorded on a 400 Megabyte optical disk for subsequent processing to locate subsurface targets. GPR data is acquired with an 8-bit digital acquisition system. During data collection, the 300 MHz transmitting and receiving antennas are translated along a survey line across the study area. The antennas are activated at 500 ns intervals, injecting a pulse of electromagnetic radiation into the earth. The returning energy is digitally sampled to produce a 256 sample trace of the response. A complete radar profile consists of a series of adjacent traces, each of which represents the radar energy return from a vertical slice in the earth. Trace spacing is often uneven due to such factors as erratic towing speeds and variable terrain, requiring a rescaling of the traces to a uniform spacing prior to the application of data processing algorithms. To achieve this, a tick wheel is mounted on the antenna vehicle to provide an accurate measure of the distance traveled along the track line, and is used to normalize the radar data to a uniform 3-inch trace spacing through a simple interpolation routine. Field data is transferred via optical disk to a command center computer, on or off site, for immediate analysis, processing and map making.

To meet mission objectives of clearing and releasing for alternative use potentially millions of acres of former bombing and target ranges across the US, a major technological advance over currently employed methods is necessary. Because no GPR locators are approved for service use, trained EOD personnel now perform range clearance operations with standard issue MK22 or MK26 locators, which are handheld magnetometers with visual and audible indicators of local magnetic anomalies caused by buried ferrous ordnance. Operator fatigue, high false alarm rate, and narrow sweep width limit the effectiveness of this method to small, well defined areas. RADAR is designed to be operated by trained operators in conjunction with EOD range clearance operations. RADAR offers rapid and accurate survey capability with archival records. Large tracts can be searched with quantitative accuracy to yield maps of target locations and missed areas using this system.

Particularly sensitive to metal targets, GPR can also detect non-metallic targets, geological features, water tables, utility lines, and voids.

The mobile command center houses the post processing computer and peripherals. The RADAR processing scheme has three major components: data processing, image processing, and target identification. Due to the similarity between GPR and seismic data, existing data processing algorithms for enhancing and correctly imaging subsurface seismic data were adapted and applied. Advanced research efforts in machine vision were also adapted for automatic target feature extraction. The unique processing scheme locates subsurface targets in RADAR data both automatically and interactively.

Data processing begins with a preprocess routine that inputs survey data from the optical disk. GPR data from each antenna are demultiplexed and spatially normalized, using the tick wheel distance information. Navigation and tick wheel data are stripped and stored in separate files. When preprocessing is completed, a traverse map showing the path that the antenna array traversed is available for output. This map provides a quick look at the area covered and identifies missed areas that may require additional surveying.

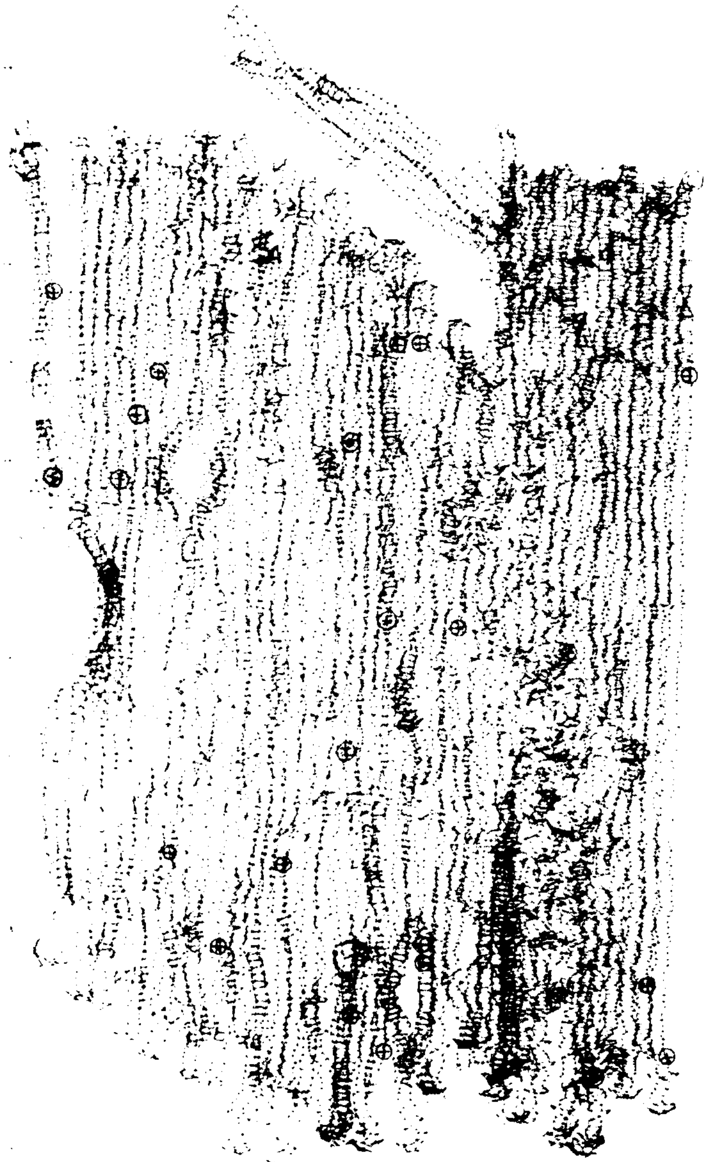
For the first time, range clearance officers can "view" spatially normalized RADAR images which provide detailed, non-destructive information concerning the subsurface character of the survey area. Interactive data analysis routines allow an operator to rapidly identify ordnance/target signatures and geologic structures. Certain targets are selected for interactive GPR propagation velocity analysis. Accurate knowledge of this variable is required for data processing and target depth determination. Using a computer mouse to match a computer generated hyperbola to the normalized target signature, the GPR velocity for that part of the survey area is uniquely determined. The operator can also interactively select targets for "same day" output. Upon completion of this data processing, an interactively selected target map, its associated target report, and the site velocity report are available for output.

Data processing continues with the application of a horizontal filter which eliminates the strong horizontal banding prevalent in GPR data. A migration algorithm then operates on the filtered data to increase target signal-to-noise ratio and to focus GPR energy from subsurface targets.

The image processing component applies two independent algorithms to locate regions of anomalously high amplitude which characterize migrated targets. Each algorithm detects and logs potential targets that exceed its mean value by one standard deviation for that line of data.

Target identification is based on a statistical correlation between the results of the two image processing techniques and an algorithm which discriminates between ordnance targets and geologic features. The final target detections are logged with each of their image processing values compared to the screening detection thresholds. Using the interactive data analysis routines allows an operator to reset the detection thresholds higher (> 1 standard deviation). The operator can then resort targets, without reprocessing the GPR data, to screen for the most likely targets. This facilitates prioritizing final target selections for relocation and clearance.

This demonstration Ground Penetrating Radar Ordnance Search System successfully performed large area surveys of test sites seeded with ordnance in California, Maryland, and Massachusetts. Throughout these tests, RADAR operated as designed. Large areas contaminated with ordnance can indeed be surveyed quickly and accurately. Targets as deep as 4.5 meters (15 feet) have been successfully detected at the Massachusetts test site where thirty-three of the thirty-four targets were located, i.e., 97% success rate, to within ± 1 meter (3.2 feet) of their actual location. Detailed records, both reports and maps, are automatically generated delineating site survey and clearance activities. Automatic data and image processing, though currently processor time intensive, provides accurate and consistent target selections. Interactive data analysis routines yield same day or overnight results. The system and the technology has demonstrated a wide range of application to ordnance location as well as to environmental pollution survey requirements.

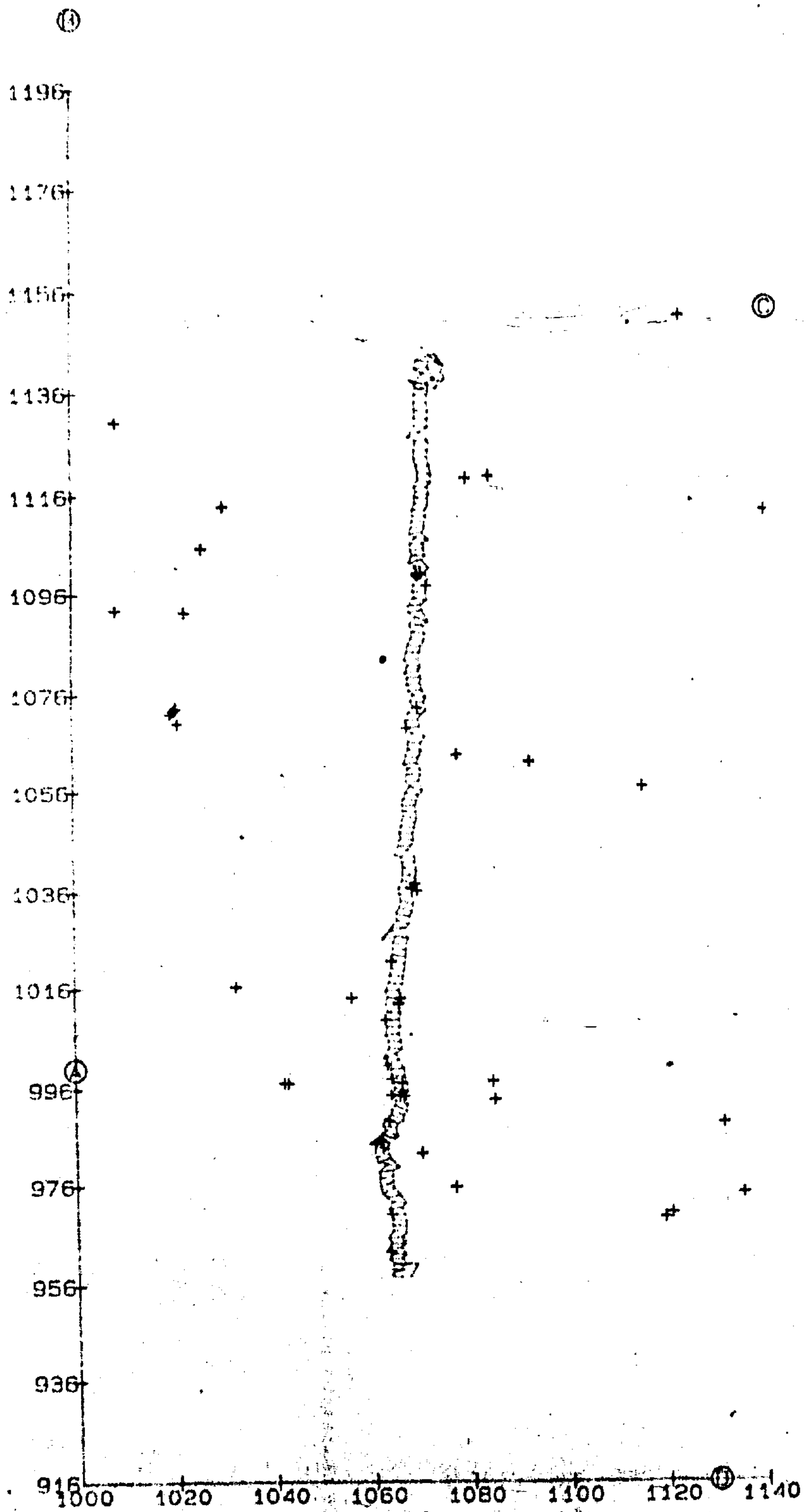


GEO-CENTERS, INC

Tue May 22 13:48:05 1990

29 Palms TARGET MAP (TPT2)

BEACONS:
A - 1000, 1000
B - 1000, 1210
C - 1140, 1153
D - 1130, 916



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Ground Penetrating Radar Ordnance Search System (RADAR)

RADAR is an automated ground penetrative radar array based ordnance locator system employing proven technology for rapid and reliable reconnaissance of large contaminated areas. RADAR is designed for operation by trained personnel in conjunction with trained Explosive Ordnance Disposal and Civil Construction Engineering personnel.

Developed by

Naval Research Laboratory,

Naval Explosive Ordnance Disposal
Technology Center

and

GEO-CENTERS, INC.
Newton Centre, Massachusetts
for
U.S. Army Corps of Engineers

RADAR Tow Vehicle and Platform

The RADAR Tow Vehicle and Platform are a complete automated mobile field system for rapid range clearance. The Tow Vehicle is a customized, general purpose four wheel drive prime mover. Designed for two operators, it carries the RADAR controller, a computerized data acquisition system with optical disk storage, the microwave positioning system, and a track guidance display unit.

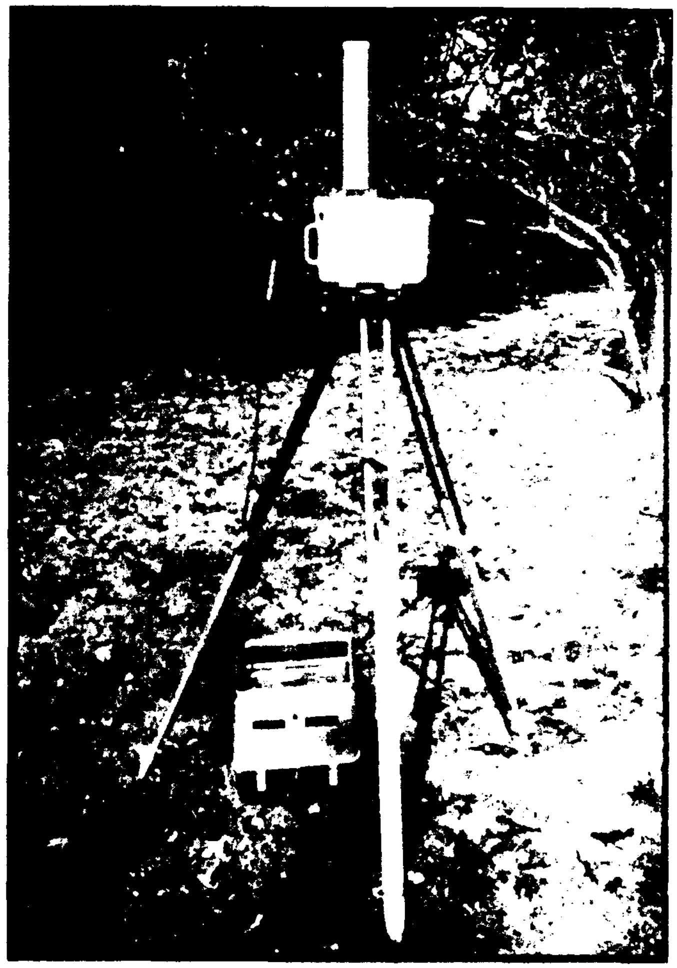
The RADAR Platform provides mechanical and electrical support for an array of four Ground Penetrating Radar (300 MHz) antennas. The onboard AC generator supplies power for the Tow Vehicle systems. A compressor provides pneumatic power for antenna position control.

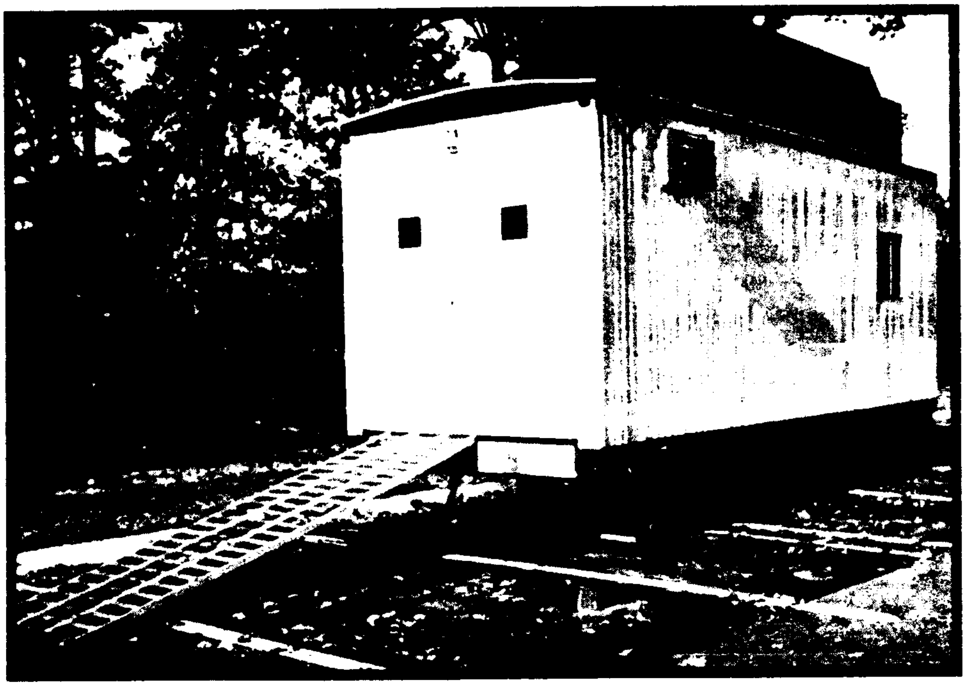
RADAR in Transport Mode

Designed to float over rugged terrain, the antennas raise and fold for storage and highway transport.

RADAR Remote Navigation Station

Four stand-alone remote stations serve as navigation beacons for the microwave positioning system on the RADAR Tow Vehicle. Accuracies of ±1 M are attained. Rechargeable battery packs provide 24 hour continuous operation. Each remote station is interchangeable with the master transceiver on the RADAR Tow Vehicle.





RADAR Command Center

The RADAR Command Center is an environmentally controlled shelter, ruggedized to be transportable by land, sea or air. The data processing system inside generates target maps and reports on-site using either commercial power or external generators. Storage is provided for system components and supplies, including the RADAR Platform.

RADAR Specifications

Survey Range:	20 acres per day
Target Location (X,Y):	± 1 meter
Target Location (Z):	± 1/3 meter
Reference Target:	500 lb bomb, 4.5 meters deep
Operating Temperature:	+32° F to + 110° F
Operating Humidity:	0% to 99%
Operating Weather:	moderate rain, dust, wind and terrain

1.0 INTRODUCTION

The US Congress, through Public Law 98-212, charged the Department of Defense to institute a remedial action program to clear ranges and areas contaminated with hazardous explosive materials and ordnance. As part of the response, the U.S. Army Corps of Engineers tasked the US Navy, as the lead service in Explosive Ordnance Disposal (EOD), to develop and demonstrate different systems each capable of detecting, locating, and partially identifying shallow buried, unexploded ordnance. The Naval Explosive Ordnance Disposal Technology Center (NAVEODTECHCEN), through the Naval Research Laboratory (NRL) and various contractors, reviewed current technology and identified three technological approaches offering high promise of success on a responsive time scale: 1) surface electromagnetics, 2) surface magnetometry, and 3) borehole magnetometry/electromagnetics. Surface electromagnetics (Ground Penetrating Radar) is the subject of this report.

The Ground Penetrating Radar (GPR) Ordnance Search System (RADAR) is a tailored array of commercially-available electromagnetic GPR antennas towed by a four wheel drive vehicle. Data acquired in the field is transferred via optical disk to a command center computer, on or off site, for immediate analysis, processing and mapping.

Since the Corps of Engineers program was an Advanced Development effort, the thrust of the RADAR development was directed to the application, where possible, of existing technology. Critical paths to success, based upon speculative approaches, were to be minimized; although parallel efforts providing for system upgrade were acceptable. To achieve this end, the research effort was divided into the following tasks:

- Electromagnetic models
- GPR antenna evaluation and selection
- Mechanical system development
- Data acquisition system development
- Data processing software development
- Field demonstrations

The traditional method of GPR field operations involves translating a single GPR transmitter-receiver antenna configuration along a survey line by hand. The resulting analog signal is directed to a magnetic tape recorder or an electrostatic plotter for display and interpretation by visual inspection. Survey speeds must be kept slow to minimize uneven traces which distort the subsurface image. Unprocessed GPR data is further complicated by signal ringing and reverberation, reflection from geologic structures, and noise. Evaluation of the data through visual inspection therefore requires a skilled interpreter which is both time consuming and expensive. In order to reduce expense, survey line spacing is typically large thereby limiting the survey resolution. Further, visual inspection of the data is subject to non-uniform interpretation and the introduction of operator bias.

To meet mission objectives of clearing and releasing, for public use, potentially millions of acres of former bombing and target ranges across the US, a major technological advance over existing methods was necessary. Because no GPR locators are approved for service use, trained EOD personnel perform range clearance operations with the standard issue MK22 or MK26 locators. Both are hand-held magnetometers with visual and audible indicators of discovered local magnetic anomalies. Operator fatigue, high false alarm rate and small sweep area limit the effectiveness of this method to the detection of ferrous metal targets in small, well defined areas. RADAR, a four antenna array system by

comparison, offers rapid and accurate survey capability with archival records and the additional ability to detect both metallic and non-metallic targets as well as geological features. For the first time, hundreds of acres at a time can be swept with quantitative accuracy to generate listings and maps of target locations and missed areas.

Work performed in a previous contract provided the theoretical basis and contributed many engineering concepts for the developmental prototype RADAR. Application of GPR technology to range clearance was validated through a series of development efforts including:

- GPR antenna development and modeling
- Digital data acquisition and storage
- Data processing
- Field demonstrations

Detailed results of these efforts were presented in a technology validation report, highlights include:

- A recommendation to use commercially available GPR antennas
- The development and field testing of an interim (single channel) digital data acquisition and storage system
- The development and evaluation of preliminary processing algorithms and utilities
- The development of a catalog of digital GPR/Ordnance data from three test sites

Together, these efforts formed the basis of a conceptual design for a multi-antenna array GPR Ordnance Search System. Field test results validated GPR as an effective range clearance technology. Within its operational constraints, GPR is a superior search tool for detecting metallic and non-metallic targets, otherwise invisible to other survey technologies.

This final report covers the performance on contract NC-00014-86-C-2266 from October 1986 to October 1990.

2.0 SYSTEM DESCRIPTION

RADAR is an automated, multisensor array, on and off-road, ordnance locator system, whose mission objectives are to:

- Detect and locate buried ordnance to a nominal depth of 15 feet
- Conduct surveys of contaminated areas at the nominal rate of twenty acres per day
- Generate hard copy site and target maps (see Figure 15)

RADAR is designed to be operated by trained personnel in conjunction with EOD operations.

The top level tree structure, Figure 1, shows that RADAR consists of five major components: RADAR Tow Vehicle (RTV), RADAR Tow Platform (RTP), Remote Navigation Stations (RNS), RADAR Command Center (RCC), and System Support. The RADAR block diagram in Figure 2 reveals the central importance of a mobile subsystem made up of the tow vehicle and platform. Here reside all the equipment and instrumentation for collecting GPR field data over a survey area. Remote navigation stations maintain radio links to the tow vehicle for accurate position fixes. At the conclusion of a field data acquisition survey, RADAR data are transferred via removable optical disk to the command center computer for processing and analysis.

The navigation system provides accurate information for conducting precise systematic surveys and tags data for target location and relocation. The customized Radar Controller acquires four (expandable to eight) channels of GPR data digitized to 8 bits. During data collection, the 300 MHz antennas translate along

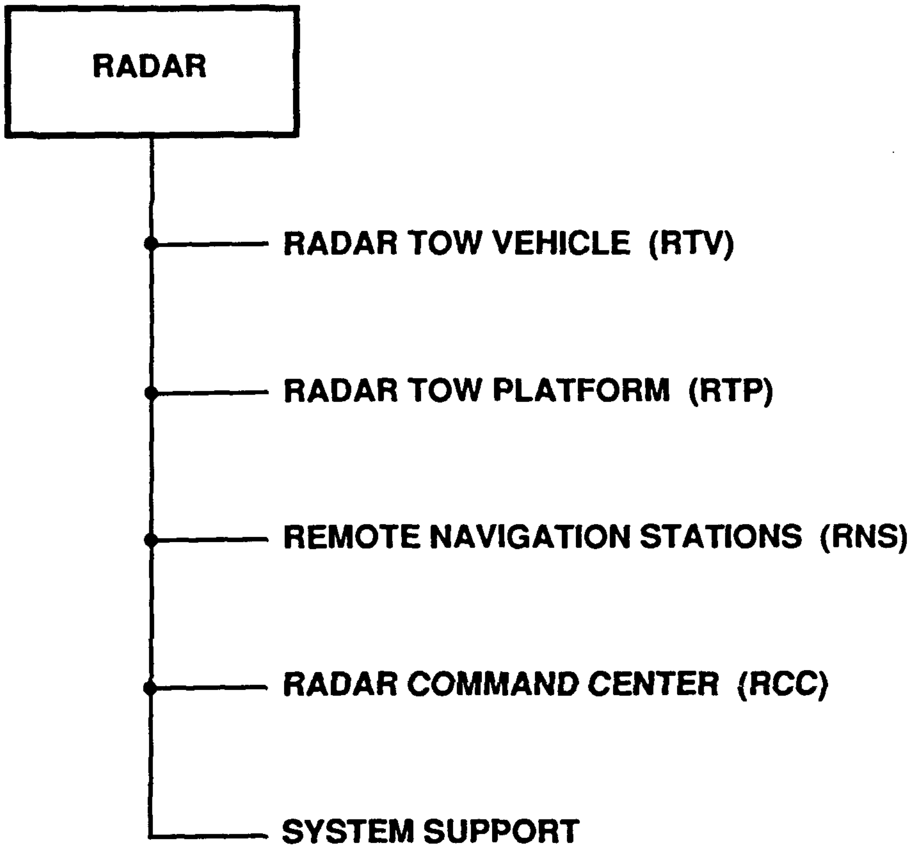


Figure 1.

RADAR Top Level Tree Structure
Major Components

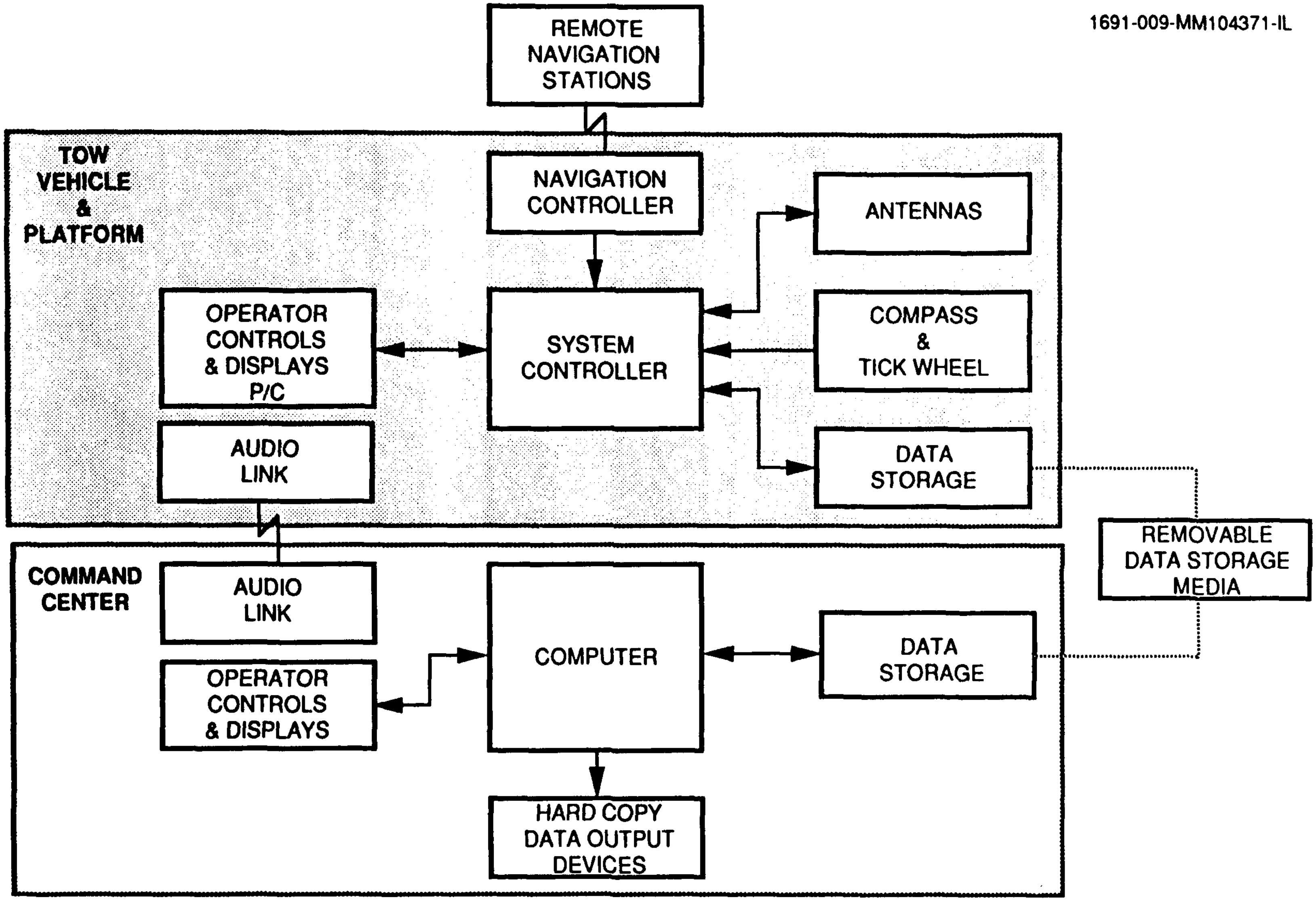


Figure 2.

RADAR Total System Block Diagram

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a track line. They are activated at 500 ns intervals, injecting a pulse of electromagnetic radiation into the earth. The returning energy is acquired producing a 256 sample trace which is stacked or averaged by a factor of eight for improved signal to noise. A complete radar profile consists of a series of adjacent traces, each of which represents the radar energy return from a vertical slice in the earth. A custom Operator Control and Display Computer controls, displays, and stores survey data. Advanced data and image processing algorithms provide unique operator interactive insights into the site subsurface character as well as consistent, automatic target detection and location to ± 1 meter in x and y, and ± ½ meter in depth (z).

2.1 Hardware

2.1.1 RADAR Tow Vehicle (RTV)

The RTV is a specially modified Dodge four-wheel drive vehicle. The RTV serves as the support platform for the data acquisition equipment, as prime mover for the tow platform, and as a field support vehicle with storage of the Remote Navigation Stations (RNS) and battery charging facilities for RNS battery packs. The tree structure of the RTV is shown in Figure 3.

2.1.1.1 Vehicle

The RTV is a Dodge Ram Charger with 318 cubic inch V8 engine, 4 x 4 automatic transmission with hi/lo range, air conditioning, engine oil cooler, transmission oil cooler, auxiliary engine fan, and oil pan skid guard. Tires are 15-inch, high floatation, all terrain tires operable down to 20 psi.

The RTV has been specially modified as follows:

- Equipment mounts for data acquisition and control electronics
- Positively ventilated RNS battery charging compartment
- Rear facing RADAR operator's seat

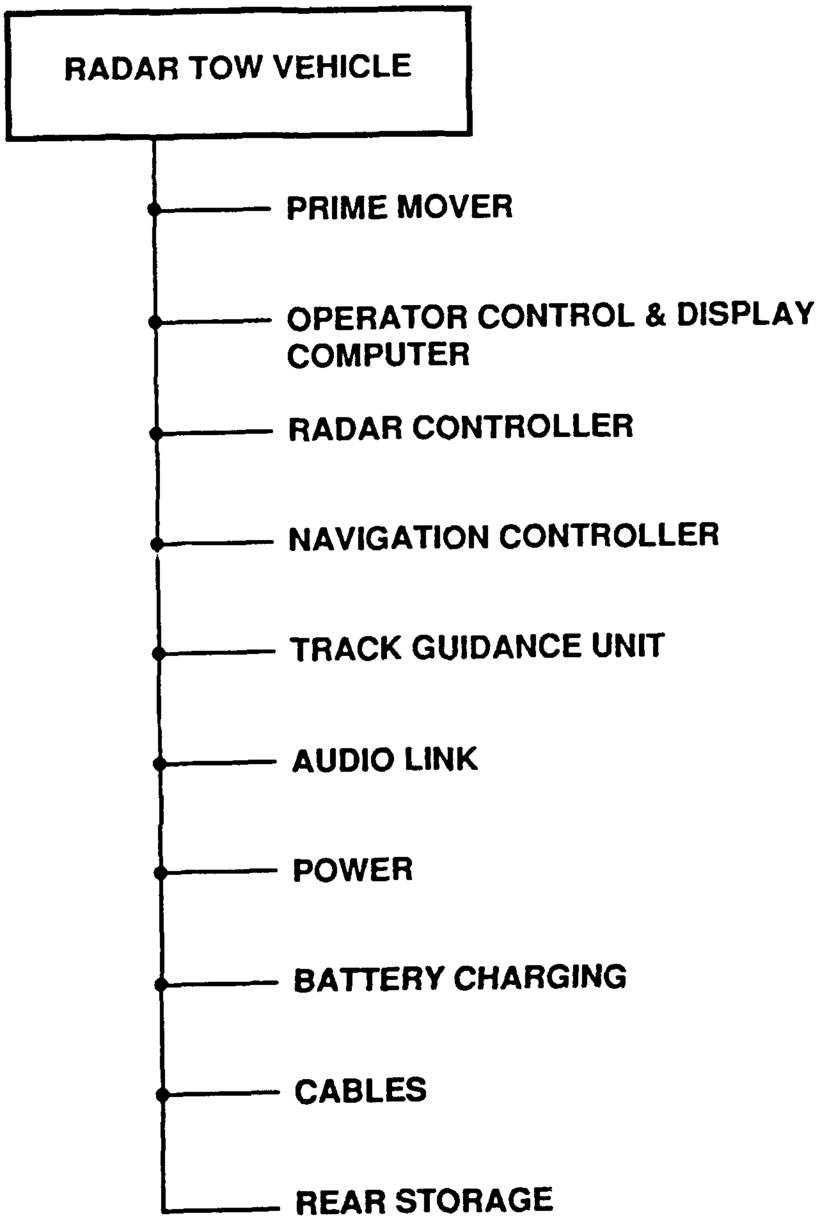

Figure 3.

RADAR TOW VEHICLE Tree Structure

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- Audio link
- Rear storage racks
- External input/output connectors
- Anti-static drag chains

2.1.1.2 Operator Control and Display Computer (OCDC)

The RADAR system operator interfaces through the OCDC which controls, acquires, formats, displays and stores field data. The OCDC is housed in a custom 19-inch rack assembly and is composed of the following:

- Ruggedized PC with Power Supply - a Diversified Technologies CAT902 286 PC and power supply serves as master controller

- I/O Board to RADAR Controller - a custom designed board provides operator control of, and acquires GPR data from, the Radar Controller

- Ruggedized Display and Controller - a Panasonic high resolution monochrome graphics monitor (512 x 400 x 8 bit) and an AT&T Targa 8 graphics board provide display of operating menus, GPR calibration data, real time GPR data from channel 0 during non-store operations, and playback of any GPR channel after an acquire cycle

- Serial I/O to Navigation and Compass - two serial interface ports on the ruggedized PC described above input navigation and optional tow platform compass data

- Development Monitor - a floor mounted monochrome monitor is provided for program start up and fault analysis

- Keyboard - Marshall Industries AT compatible keyboard provides all operator input

- Optical Disk Drive - a Schugart 5984 400 Mbyte optical disk drive stores formatted GPR, navigation, compass, and status data in archived files with unique site survey identifier and sequential file numbers. This high capacity storage media provides 80 minutes per side for the baseline (four 300 MHz GPR antennas) design.

- Hard Disk Drive - the Mini-scribe 8425S 40 Mbyte hard disk stores the application program and debugging utilities

- Backplane - a Diversified Technologies backplane routes power and signals between circuit boards

- Enclosure - the OCDC is housed in a custom 19-inch rack assembly with slide rail mounts

Front panel features include:

- Power on/off switch
- Hard reset switch
- Optical disk access
- Cooling fan and speaker grill
- Graphics monitor with brightness and contrast controls
- Keyboard connector

Rear panel features include:

- AC power connector
- Power supply fan
- Development monitor cable
- Connectors for RADAR controller, track guidance, navigation and compass

An internal junction board routes power and signal between rear panel and backplane.

On powerup, the RADAR operator interfaces through the monitor and keyboard. After entering the application program "RADAR", all menus and status displays appear on the graphics monitor in front of the RADAR operator. A series of menus steps the operator through survey set-up, GPR calibration, acquisition of survey data, playback of stored files, and selected diagnostics.

2.1.1.3 Radar Controller (RC)

The Radar Controller is a custom unit designed and built by GEO-CENTERS. It accepts operator control for time window, trace position, and range gain for each antenna. It addresses each antenna separately and is currently configured to transmit and sample each antenna sequentially. For each antenna, the controller

filters, applies the range gain and averages eight samples for a 256 point trace output. The controller also monitors and outputs the status of each radar channel and all its power supplies. The front panel contains the on/off switch, power supply monitor LEDs and a tick wheel monitor LED. The platform mounted tick wheel provides information on the distance traveled between GPR traces. This data is formatted with each GPR record and is subsequently used to spatially normalize survey data. The rear panel provides input/output connectors for AC power, platform interface, platform GPR data, and OCDC interface. All RC circuit boards are wire wrapped on standard 4 x 6 inch Eurocard development boards, and are mounted in a custom 19-inch rack enclosure. The following circuit boards are contained in the RC:

- Digital I/O (DIORC) - provides digital input/output to the OCDC described above
- Platform I/O (PIORC) - provides antenna addressing and trigger signals to the platform interface
- Timing Control Board - provides the master clock and timing signals based on operator selected values for time window (search depth) and trace position (position of transmit pulse in sampled trace)
- Transmit and Sample Trigger Generator Board - generates transmit and sample triggers based on data provided by the timing control board
- Range Gain Board - stores operator selected values for fixed gain (applied to all samples) and gain slope (exponential gain value for each sample)
- Signal Processing Board - uses an 8 bit multiplying analog to digital converter to apply the range gain values and digitize sampled GPR data. It also stacks and formats GPR and RC status data for output to the OCDC.
- High Voltage Power Supplies - a -70 VDC power supply board and a +150 VDC power supply board provide the required voltages to the commercial 300 MHz transmitters and samplers on the tow platform

- Power Supply - a commercial Lambda power supply converts 115 VAC input to required +15 VDC, -15 VDC, and +5 VDC. A separate custom regulator provides -5 VDC.
- Backplane - a custom wire wrapped backplane provides power and data links to all circuit boards
- Junction Board - routes signals and power between front panel, rear panel and backplane

2.1.1.4 Navigation System Controller

A Racal Micro-Fix on-board positioning system calculates and assigns x,y coordinates to the RTV as it moves over the survey area. The navigation data tags the location of incoming GPR data from which graphic images, maps, and target locations are subsequently generated. The Racal Micro-Fix system was selected after a comprehensive review of commercially available technologies, including microwave ranging, optical tracking, inertial guidance, and global positioning systems (GPS).

The Racal Micro-Fix operates in the 5 GHz band at 0.5 watts peak radiated power and achieves a repeatable accuracy of +/- 1 meter. The Micro-Fix comprises two principal units: a Transmitter/Receiver unit (T/R), and a Control Measurement unit (CMU). The CMU is used in conjunction with a T/R unit to form a master station controlling deployed T/R's.

Switch-on is by a single key entry, causing the CMU to enter into a self-test procedure. On completion of the self-test, the operator can enter new operating parameters or use those previously entered and stored in battery backed memory. Operator interactions with the CMU are through the front panel keypad and liquid crystal screen display.

A MENU key enables the operator to view any one of the four menu pages in turn. Dedicated keys allow the required function to be selected and displayed.

The CMU calculates an x,y position every second from ranges it receives by interrogating remote transmitter/receivers stationed around the survey area. This data is sent automatically to the Operator Control and Display Computer over an RS232 serial data cable, along with left/right steering and distance-to-go information, which are displayed on the Track Guidance Unit. The CMU is housed in a lightweight, weatherproof case, weighs 7.1 kg (14.6 lb) and operates in the temperature range 0 to 55 degrees C (32 to 131 degrees F). A custom faceplate allows it to be mounted in the 19-inch rack assembly above, the OCDC for easy access by the RADAR operator.

The CMU is connected to a master T/R (MT/R) mounted on the tow vehicle roof. Racal T/R units incorporate automatic calibration to compensate for errors due to turn around delays associated with microwave ranging systems. This calibration eliminates the need for predeployment calibration, and T/R units can be interchanged as required with accuracy maintained over the whole operating temperature range. All the T/R units are identical and operate on the same frequency. This "common unit" concept presents logistical advantages for the user. The antenna is omnidirectional, circularly polarized and features a 360 x 20 degree beam pattern. The unit weighs 7.4 kg (16.3 lb).

2.1.1.5 Track Guidance Unit (TGU)

Track guidance information is displayed to the tow vehicle operator on the TGU. This stand alone unit provides status LEDs for itself and the availability of navigation data. A left/right

meter indicates vehicle position relative to the desired track and a bank of LEDs provide meter scale information of 1,2, 5 or 10 meters per division. Tow speed information is displayed in miles per hour on a separate portion of the left/right meter. An alpha numeric display with contrast control, displays "Distance to Go" and "Distance Off Track" information. The TGU is mounted in a hooded box with side studs and wingnuts for mounting to either the dash mounted bracket for operations, or a floor mounted bracket for storage and transport. A bottom flange connector provides power and data input. The TGU consists of the following circuit boards:

- CPU Board - a single board computer serves as master to perform status checks, input navigation data, calculate survey speed and output data for display
- Display I/O Board - controls the left/right, alpha numeric and LED displays
- 5 Voltage Regulator - provides 5 V operating voltage from the 12V supply

2.1.1.6 Audio Link

An audio link is provided for communication with the Command Center and to a remote support group whose primary function is to maintain the remote navigation stations. The audio link system is a commercial VHF system manufactured by Motorola. An HT90 handheld transceiver is plugged into a vehicle communications adapter mounted on the floor between the two operator seats. A high gain (3dB) antenna is mounted on the tow vehicle roof.

2.1.1.7 Power Supply

Power for survey operations is provided by a Honda 5KW generator mounted on the tow platform. 115 VAC, 60 Hz power is supplied through a rear bumper mounted connector and routed to an ISOREG power line conditioner which provides regulated power to the

data acquisition electronics. A power monitor allows the RADAR operator to monitor input voltage, current, and frequency to and from the line conditioner. Also displayed and monitored on the power monitor is the 19-inch rack temperature. Unconditioned power is provided for RNS battery charging.

2.1.1.8 Battery Charging

A battery charging compartment is provided in the rear partition of the tow vehicle for the RNS battery packs. Power is supplied from the rear bumper connector which can be supplied by either the tow platform generator, or available line power. A rear compartment plate provides single stage charger on/off control and a rotary switch and current meter to monitor state of charge of each battery. The RNS batteries are stored in a closed shelf and a set of ventilation fans draw air both from the battery shelf and the front cab area to prevent any hydrogen gas build up.

2.1.1.9 Cables Assemblies

All cables assemblies terminate in bayonet-style connectors. Shell size varies according to the number of conductors, and inserts are uniquely keyed to prevent crossed connections. Waterproofed bulkhead connectors are provided on the tow vehicle rear pillars. The port pillar provides connection for the tow platform compass. The starboard pillar provides connections for the platform interface and radar data cables. A bumper mounted trailer connector provides trailer utility signals for highway use and for feed through of antenna up/down control.

2.1.1.10 Antenna Up/Down Control

The position of the tow platform GPR antennas are pneumatically controlled from inside the tow vehicle. Manual switches to raise or lower the antennas are located on the side of

the 19-inch rack assembly for the RADAR operator and on the front dash for the tow vehicle operator. A dash mounted display shows red when antennas are up and green when antennas are down. The antenna position is also controlled by the tow vehicle reverse switch which automatically raises the antennas for backing up the tow platform.

Detailed preparation and operation of the RTV is given in the RADAR Operator's Manual - which was delivered with the system.

2.1.1.11 Rear Storage

The rear storage area provides racks for storing the RNS in their original shipping containers. Also provided are storage of a field tool box and spare tires for both the tow vehicle and tow platform. PVC tubes conveniently house the RNS tripods and provide ample side room for storage of miscellaneous field supplies such as marking flaps, air hose for reinflating tires, and measuring tape.

2.1.2 RADAR Tow Platform (RTP)

The RTP is a custom, two wheeled trailer. A top view of the RTP is shown in Figure 4. An aluminum frame is supported by standard trailer tires, axles and leaf spring suspension. Axle bearing buddies keep wheel bearings positively lubricated and protected. The RTP serves as the platform for the four, 300 MHz GPR antenna array, platform interface, tick wheel, power generator, and pneumatic antenna control system. The RTP tree structure is shown in Figure 5.

2.1.2.1 Mechanical Frame

The frame is constructed of welded aluminum U channel and box (4 x 2 inches). The central frame houses the two central GPR antennas. Two folding outriggers contain the outer GPR antennas.

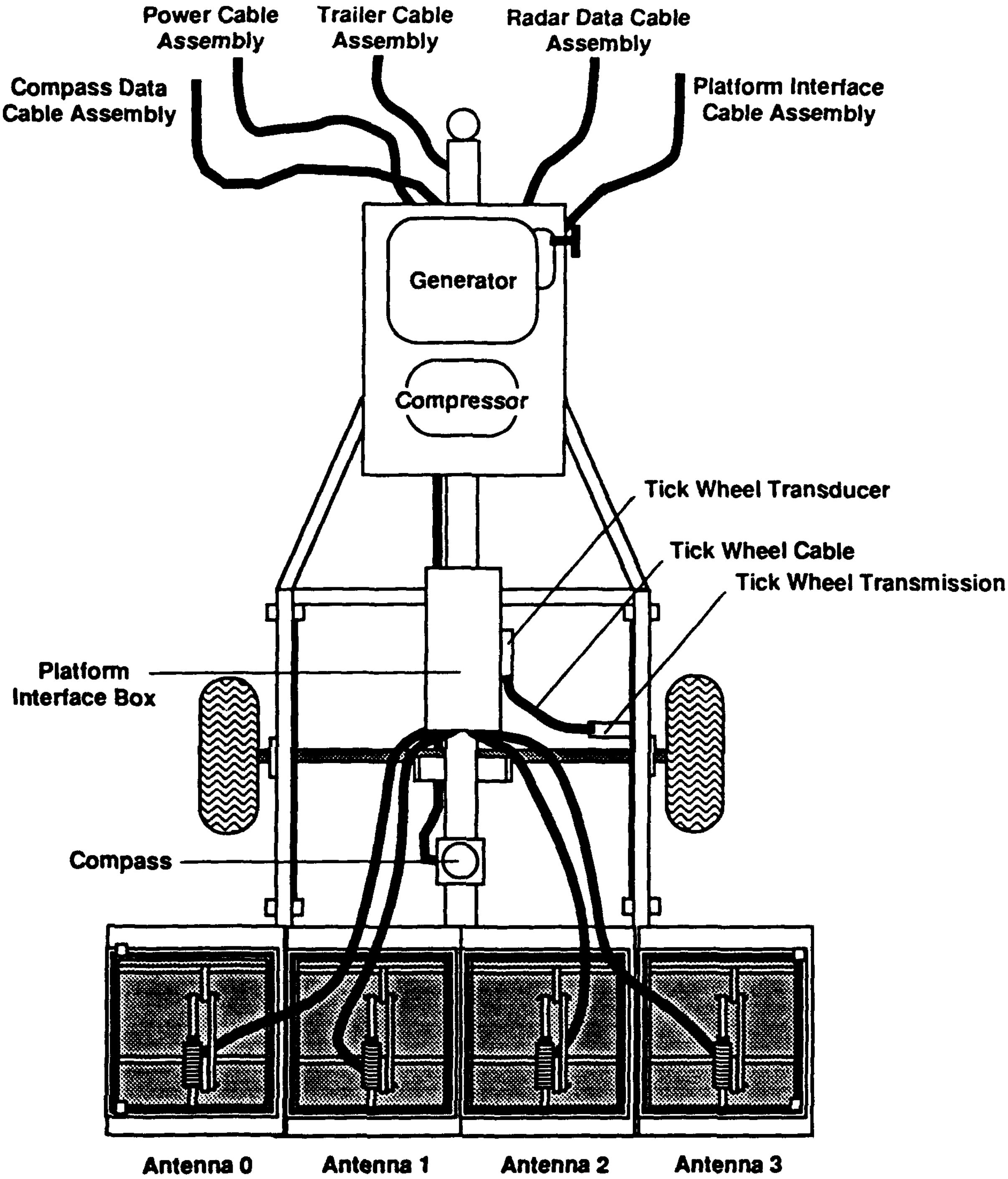

Figure 4

RADAR Towed Platform (Top View)

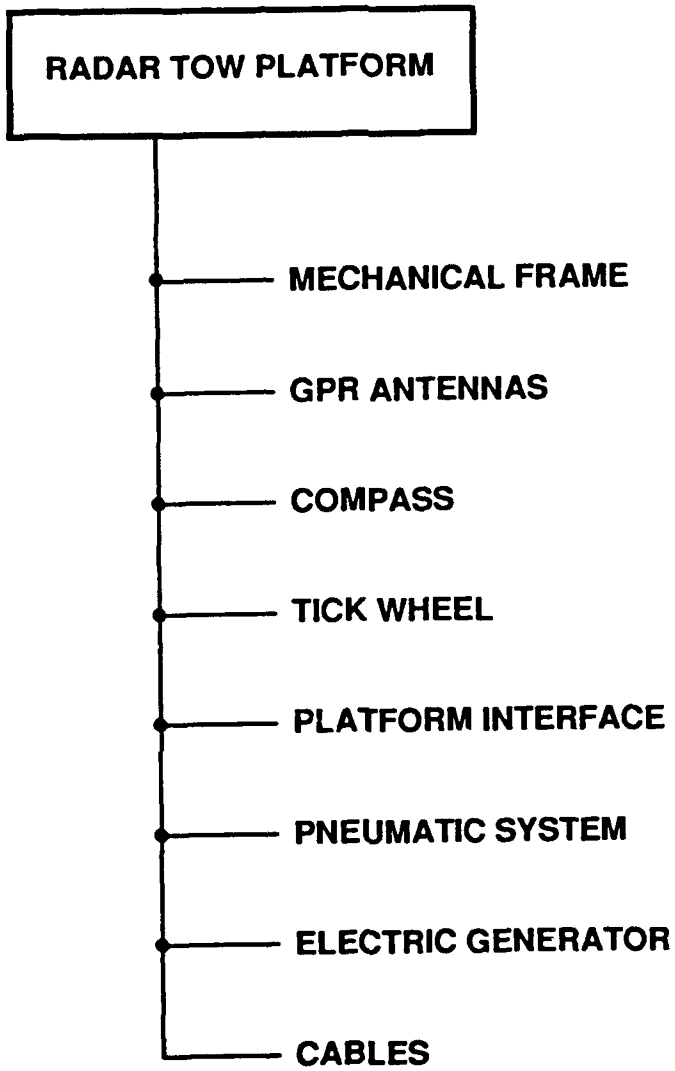

Figure 5.

RADAR TOW PLATFORM Tree Structure

Mounting of each antenna is from a pair of welded swingarms attached to the frame by pillow blocks at each corner. The pillow blocks are provided with grease fittings to maintain bearing lubrication. Pneumatic cylinders attached to the frame and each antenna swingarm assembly rod provide a shock absorbing feature that allows antennas to float freely in off-road terrain but stiffen when antennas reach their maximum travel. Pressure relief valves dampen antenna movement back down. The antennas are bolted to an aluminum frame of angle (2 x 2 inch) with a single castor in front and two casters in the rear to help prevent damage to the antenna casings. A set of lock pins securely hold each antenna in the full up position for storage and shipping. Custom aluminum hinges and standoffs allow outriggers to fold in for storage and transport. Folded outriggers are secured by rubber shock cords. Welded gussets and braces are provided at critical joints. Lead ballast is added to the forward frame to help balance the platform.

Mounts are also provided for the tickwheel, electric generator, and pneumatic air compressor. A front jack with caster is provided for lifting and moving the tow platform and a set of trailer utility lights are provided for highway use.

2.1.2.2 Antennas

The four GPR antennas are GSSI model 3105AP, operating at a center frequency of 300 MHz. Each antenna houses a transmitter and a sampler and are mounted in fiberglass shells. Antennas are mounted on 2.5 foot centers providing a total swath of 3 meters (10 feet) at the surface.

2.1.2.3 Compass

The digital compass procured is a Sailcomp Model PC103. The compass display is used as the left/right and survey speed display for the track guidance unit described above.

2.1.2.4 Tick Wheel

A tick wheel is employed to provide high resolution "distance traveled" information to spatially normalize GPR data. A Datametrics 500 ticks per revolution, optical shaft encoder is mounted in a custom Bud box on the tow platform. It is driven by a flexible shaft which is gear driven by the platform's starboard wheel. This gear drive has two positions; an engaged, locked operating position; and a disengaged, locked storage position. The later position is used to prevent damage at highway speeds. The tick wheel output is connected to the platform interface where it is combined with GPR data cables in a common cable to the tow vehicle.

2.1.2.5 Platform Interface

A platform interface box is mounted to the tow platform to provide electrical interface between the GPR antennas and the tow vehicle RADAR controller. It also serves as a cable junction box. Bayonet-style flange connectors are attached to each endplate. The front plate provides connections for the tick wheel, tow vehicle platform interface, and tow vehicle GPR data cables. The rear plate provides connectors, for each antenna. The enclosure base is rigidly mounted to the platform frame. The circuit boards contained inside are:

- Multiplex Board - demultiplexes the GPR antenna addressed by the RADAR controller
- Transmit, Sample Board - provides high voltage triggers to each transmitter or sampler as directed by the multiplex board

2.1.2.6 Pneumatic System

The pneumatic system is driven by an electric air compressor and accumulator. The pneumatic system is used to provide GPR antenna lift. The compressor is mounted on the platform frame

behind the electric generator. Air control is accomplished by a 12 VDC solenoid driven by switches in the tow vehicle or by the tow vehicle's reverse switch. Power for the air compressor is supplied by the electric generator.

2.1.2.7 Electric Generator

A Honda 5KW generator is mounted to the top of the tow platform just behind the front jack. The generator is recoil started by hand from the starboard side.

2.1.2.8 Cables Assemblies

All cables assemblies terminate in bayonet-style connectors. Shell size varies according to the number of conductors, and inserts are uniquely keyed to prevent crossed connections. Cable guides and protective PVC tubes are provided at strategic points reduce the risk of cable damage.

Procedures for RTP setup and breakdown are provided in the Operator's Manual. Figure 6 shows the tow vehicle and tow platform in transport and operational modes.

2.1.3 Remote Navigation Stations (RNS)

Four remote navigation stations are deployed around the survey area during RADAR field operations. These Racal Transmitter/Receivers (T/R) are stand-alone stations which establish and maintain line-of-sight radio links with the master T/R on the RTV, by which accurate ranges are determined and position fixes of the RTV are calculated. The tree structure for the RNS, Figure 7, shows four components.

2.1.3.1 Transmitter/Receiver (T/R)

T/R units deployed as remotes are preset to the common chain code 1. This first digit chain code uniquely, identifies the

Figure 6.

RADAR Tow Vehicle and Tow Platform
(Transport and Operational Modes)

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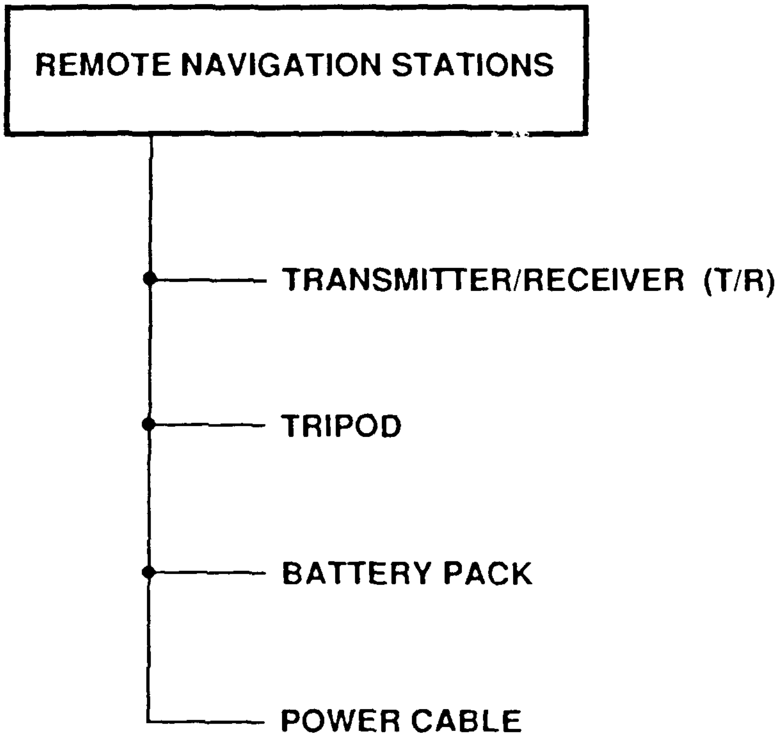


Figure 7.

REMOTE NAVIGATION Tree Structure

master T/R as one of potentially sixteen vehicles operating simultaneously in the same site with the same set of reference T/Rs. T/Rs are also preset to their own unique station codes, which are 01, 02, 03, and 04.

Each T/R unit is interrogated 220 times a second by the master T/R on the tow vehicle, which has the identity code 100. On each interrogation cycle, the master T/R unit transmits a lock pulse followed by a time-related station code pulse. A remote station recognizing its own station code replies to both these pulses, thus providing two sets of range data in each interrogation cycle. Each reply comprises two pulses whose spacing is dependent upon the turn around delay (TAD) of that remote unit and is, in effect, its TAD signature. The reply pulses received by the MT/R are passed to the CMU, where numerical processing subtracts the TAD to provide a corrected range. As this self-calibration is continuous, the accuracy of each remote T/R is maintained over the entire operating temperature range of -30 to 70 degrees C (-40 to 158 degrees F). The requirement for pre-deployment calibration is therefore eliminated and allows all T/R units to be interchangeable.

2.1.3.2 Tripod

The T/R mounts to a standard tripod which elevates the antenna approximately 2 meters (6 feet) above the ground. In rough, terrain where local topography prevents radio line of sight a means of elevating the RNS is required.

2.1.3.3 Battery Pack

The 10 watts of power required for operation is supplied by a custom rechargeable 24-volt battery pack, which includes a power switch, DC volt meter and DC ammeter. The pack is designed for continuous operation for more than 12 hours.

2.1.3.4 Power Cable

The 5-meter power cable with one prefabricated connector is supplied by Racal. A custom bayonet-style connector at the other end attaches to a flange connector on the side of the battery pack.

The preparation and operation of the RNS is given in the Operator's Manual. Figure 8 shows an operational RNS.

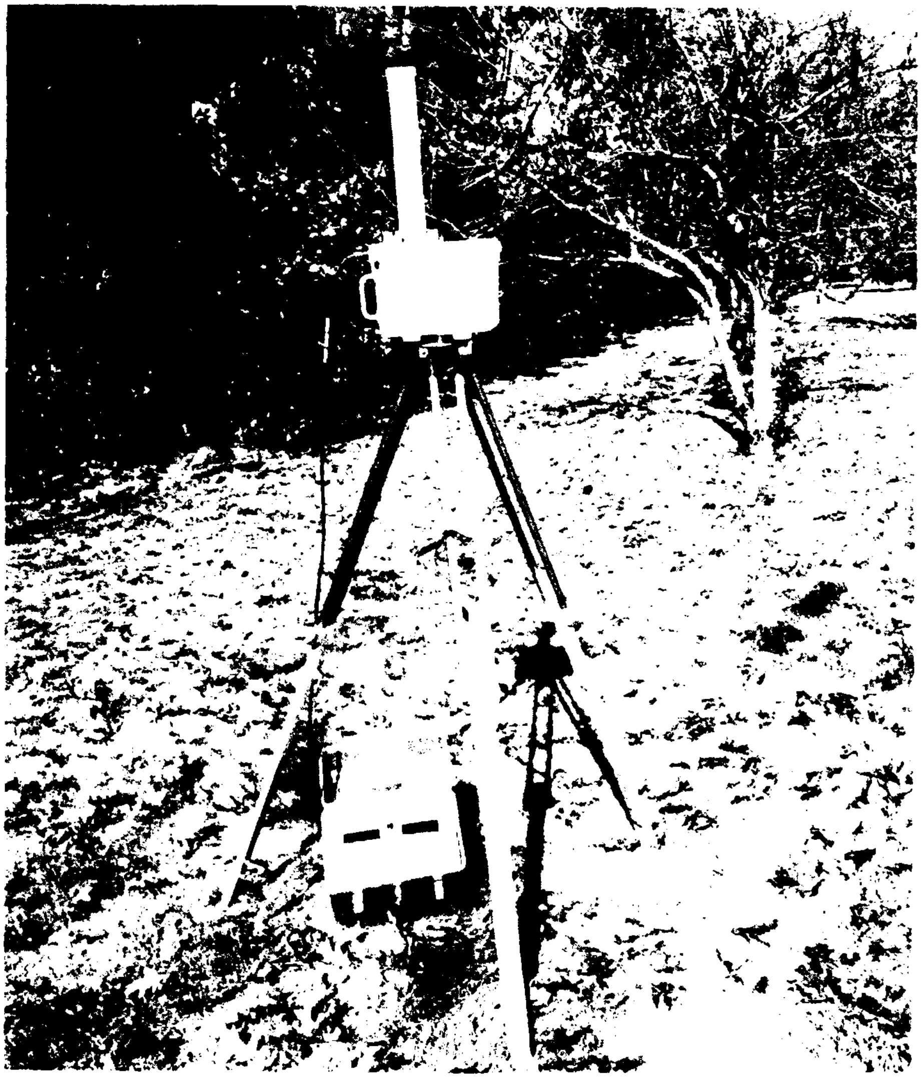
2.1.4 RADAR Command Center

The RADAR Command Center (RCC) is an environmentally controlled enclosure for the electronic data processing system and for the storage of RADAR equipment. It is designed to be transportable by land, sea, or air. It also serves as survey command post and maintenance facility. The tree structure for the RCC is shown in Figure 9.

2.1.4.1 Enclosure

The enclosure is a ruggedized Gelco, Inc. mobile office (8 x 8 x 24 feet). Special features supplied by Gelco include double steel I beam frame with dual axles, leveling jacks, full 2 x 4 inch wall and roof studs, insulated walls and ceiling, tiled floor, full width rear steel doors, two electric heaters, two window/wall air conditioners, two electric circuit breaker boxes and specially placed outlets, three windows, and fluorescent ceiling lights. As delivered, the enclosure needed additional bracing around the double rear doors to prevent racking during shipping. A brass grounding rod and cable keep the RCC frame at local ground.

The RCC interior was furnished with benches, cabinets, electric winch, magnetic white boards, alarm system, first aid kit, fire extinguisher, computer and peripherals, and is shown in Figure 10. A set of five ramps provide access. Note in Figure 11 that



RADAR Remote Navigation Station
(RNS)

- Stand-alone Microwave Navigation Transponder
- Rechargable Battery Pack for 24 Hour Operation
- Interchangeable with Master Transceiver on Tow Vehicle

Figure 8.

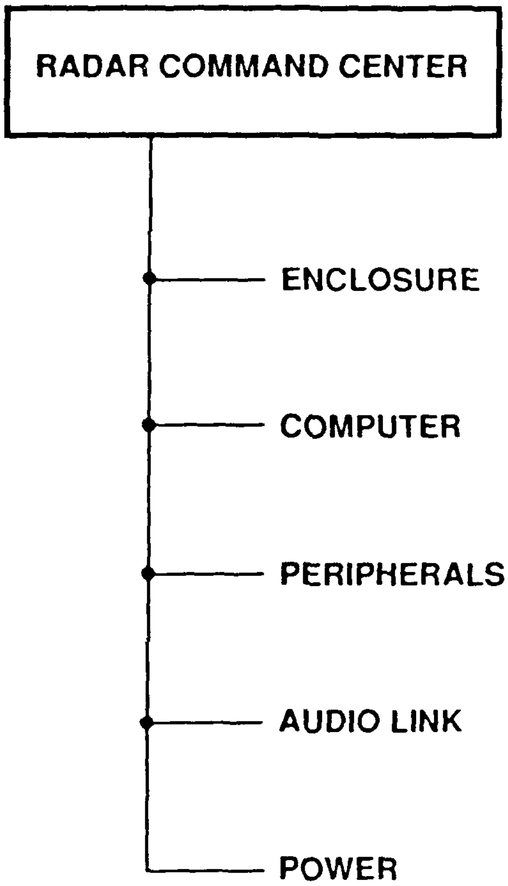
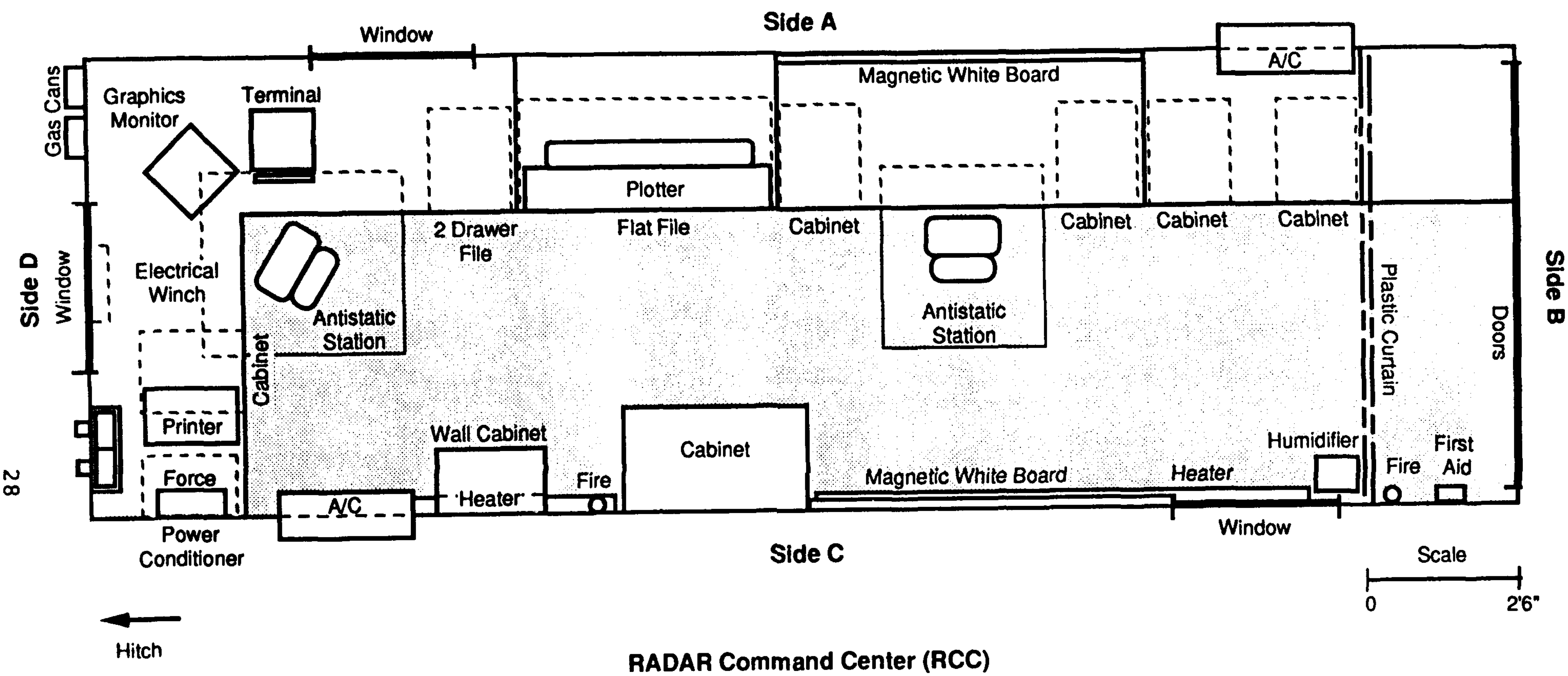


Figure 9.

RADAR COMMAND CENTER Tree Structure



RADAR Command Center (RCC)
Interior (Operational)

- **Environmentally Controlled Shelter**
- **Data Processing System**
- **Field Survey Equipment Storage**
- **Transportable**

Figure 10.

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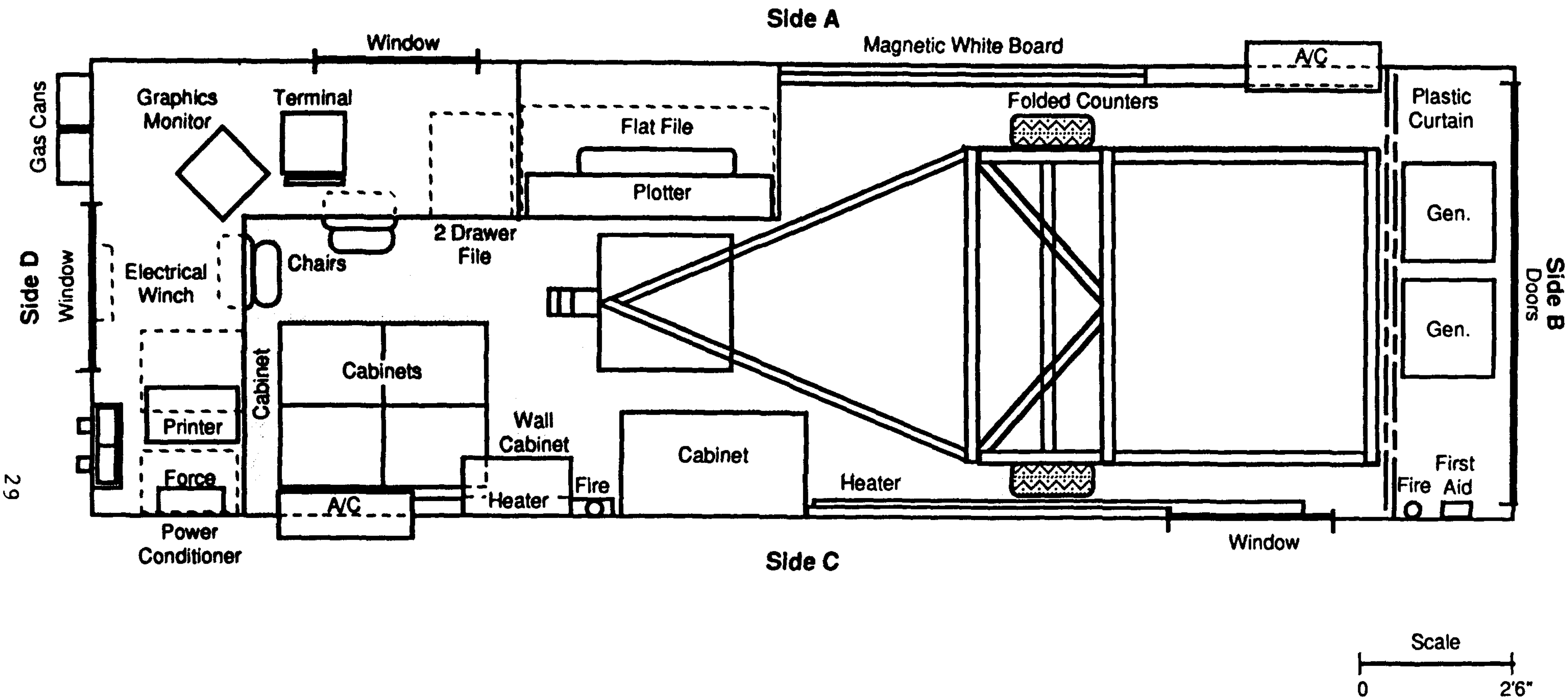

Figure 11.

RADAR Command Center Interior (Storage)

GEO-CENTERS, INC.

the two rear counters fold down and secure for long term storage and shipping of the tow platform inside the RCC. It contains antistatic stations, a plastic curtain, and a humidifier, added to minimize the risk of static discharge to computer and peripherals. Strategically located tie down locations are provided in the floor for securing equipment during shipping.

Detailed set up and operating procedures are described in the Operator's Manual. Figure 12 shows a portion of the command center exterior.

2.1.4.2 Computer

The RADAR computer is from Force Computers, Inc., which specializes in products based on Motorola 68000 series semiconductors in the widely used VMEbus standard format. The VMEbus architecture was discussed and recommended at the System Design Review in 1987. At a time when the processing requirements of the computer system were still being defined, VMEbus offered clear advantages over competing computing systems. Its open architecture permits complete freedom to configure and expand the system to meet specific requirements. By virtue of being an accepted standard, a large variety of compatible VMEbus products, such as memory and input/output boards, are available from numerous manufacturers.

Force was chosen over Motorola's computer system on the basis of performance and cost. Force offered a completely integrated, working system. Motorola offered only individual components for integration by the purchaser. Force offered support for products from other manufacturers, whereas Motorola did not. Force specifications showed a performance advantage of a factor from 1.5 to 2 in processing power over Motorola. Force had an extensive and

Figure 12.

RADAR Command Center Exterior

GEO-CENTERS, INC.

visible support system in place for its integrated systems. Finally, the price quote from Force was lower than the one from Motorola.

The system consists of the following:

- CPU-21: Advanced 68020 microprocessor
- ASCU-1: Advanced system controller
- ISCSI-1: SCSI input/output controller
- AGC-1: Advanced graphic controller
- ISIO-1: Serial input/output controller
- SRAM-22: 512 KB static RAM
- MM-6230D/16M: 16 MB RAM board
- 170 MB hard disk drive
- Moth-21: 21 slot backplane
- 400 MB optical disk drive
- 1 MB floppy disk drive
- PWR-20 power supply
- Schroff chassis and enclosure

RADAR runs the UniFLEX operating system from UniFlex Computing (formerly Technical Systems Consultants), recommended by Force for supporting a real time, multiuser environment. Besides the operating system, software from UniFLEX includes:

- C compiler
- Fortran compiler
- 68000 assembler
- Screen editor
- AGC driver
- Utilities

The computer is shock mounted to a custom base plate with casters and a set of slide rails under the front counter. Power is controlled by a wall switch.

2.1.4.3 Peripherals

The Force computer is connected to a number of external peripherals, listed below:

- Wyse WY-85 terminal and keyboard as the primary operator interface to the computer
- Datasouth DS-400 dot matrix printer for fast printouts of the SITE LOG, TARGET REPORT, VELOCITY REPORT and OPTICAL DISK DIRECTORY OUTPUTS
- Hewlett Packard HP7570A pen plotter for high resolution C-size plots of TRAVERSE MAP and TARGET MAP outputs
- Hitachi high resolution (1024 x 800 x 8 pixels) RGB color graphics monitor to display RADAR field data as grayscale images
- Logitech mouse to control a crosshair cursor on the graphics monitor for target analysis functions

2.1.4.4 Audio Link

A similar VHF audio link described for the tow vehicle is installed in the RCC. In addition to the Motorola HT90 transceiver, vehicle communications adapter, and high gain (3dB) antenna, a multi-unit charger is secured to a wall shelf for charging up to six HT90 units. A 10 amp automobile charger is provided to periodically charge the 12V battery.

2.1.4.5 Power

Power for the RCC is supplied by two Honda 5KW generators. These generators are identical to the one mounted on the tow platform and are stored inside the RCC for shipping. For operation, they are located up to 100 feet from the RCC to minimize noise. Two 30.5 meter (100 foot) extension cords connect the generators to exterior electric input boxes mounted on the RCC front wall. The RCC requires two sources of 220 VAC which may be supplied by the two generators or available line power. One source powers RCC heating and air conditioning and unregulated outlets and lights. The other source is connected to an ISOREG power line conditioner and supplies regulated power to the Force Computer and terminal. A wall mounted power monitor allows an operator to observe both power into and out of the line conditioner. In addition it also monitors and displays the Force computer chassis temperature.

Preparation and operation of the RCC is given in the RADAR Operator's Manual.

2.1.5 System Support

In addition to the major system components described above, support equipment, spares, expendables, and system documentation are provided to insure successful operations.

2.1.5.1 Equipment

The following support equipment are provided:

- Tool boxes in the tow vehicle and command center supply hand tools to effect most mechanical repairs
- Remote navigation site staking flags - located in tow vehicle provide temporary marking of beacon locations
- Battery chargers - located in tow vehicle and command center charge system batteries
- Tarp - located in the tow vehicle provides cover for temporary storage of the tow platform out of doors
- Air line (20 feet) with in-line pressure gauge - located in the tow vehicle allows tow vehicle tires to be reinflated by the tow platform compressor
- Grease gun - located in the RCC is used to maintain platform bearings
- Electric drill - located in the RCC to be used as required
- Extension cord - located in the RCC to be used as required; most often used to charge RNS batteries

2.1.5.2 Spares

The following spares are provided:

- One 300 MHz GPR antenna
- One each of GEO-CENTERS fabricated circuit boards:
  - Track Guidance Boards
    a. Single board computer (SBC)
    b. Display input/output
  - Operator Control and Display Computer Boards
    a. Radar serial interface board (RADSIB)
    b. Junction board

- Radar Controller Boards
  a. -70 VDC power supply
  b. +150 VDC power supply
  c. Computer input/output
  d. Timing control
  e. Sampling and transmit trigger
  f. Range gain control
  g. Signal processing
  h. Platform input/output
  i. Junction board
  j. Backplane

- Platform Interface Boards
  a. Transmit and sample (Tx, St)
  b. Multiplexer
  c. Junction board

- Two RNS batteries
- Miscellaneous wire and connectors
- Platform hardware and spare tire

2.1.5.3 Expendables

The following expendable supplies are provided:

- Sixteen optical disks
- Printer and plotter paper, pens, and ribbons
- Electrical fuses, tape, solder, contact cleaner
- Grease
- Paper towels and trash bags
- White board markers

2.1.5.4 Documentation

The following documentation is provided:

- System operator manuals - Volumes I and II
- Software documentation
- Priority 1 mechanical and electrical drawings
- OEM equipment manuals including Force, UniFlex and Racal navigation manuals

2.2 Software

2.2.1 Tow Vehicle Software

The tow vehicle software consists of two major programs for the operator control and display computer (OCDC), and the Track

Guidance Unit (TGU). The OCDC program "RADAR" is written in Microsoft assembly language. The compiled code is stored on the internal hard disk drive. The TGU program is written in 8088 assembly language. Its compiled code is written into erasable programmable read-only memory (EPROM) for the single board computer.

2.2.1.1 OCDC Software

The OCDC software controls all aspects of RADAR data acquisition. Setup routines prompt the RADAR operator through site setup and GPR calibration. Input routines accept and format GPR and navigation data through a pair of "ping pong" buffers and display real time GPR data from the port antenna. The storage routine writes survey and status data to optical disk. This routine also displays the number of free blocks remaining on the optical disk and increments sequential file numbers. The playback program displays raw GPR data from an operator selected file and antenna. Developmental diagnostic routines allow an operator to display the optical disk directory and check for and repair unclosed files on the optical disk.

OCDC main menu selections include:

- Acquire
  - prompts operator through GPR calibration
  - inputs GPR and Navigation data
  - displays raw GPR data (in non-store mode)
  - stores survey and status data in sequential files on optical disk
- Diagnostics
  - allows testing and display of navigation and compass data during development - currently disabled
- Playback
  - reads and displays selected GPR data from selected file

- Reset
  - performs soft program reset during development - currently disabled

- Setup
  - prompts operator for site identification code and file number for storage or playback

Detailed procedures for running OCDC software are provided in the Operator's Manual.

2.2.1.2 TGU Software

The TGU application is a fixed (no operator input) program. On power up, it performs a power on self test which initializes memory, executes self diagnostics and drives a front panel status LED.

The program accepts input from the navigation system and drives a front panel navigation status LED. The program calculates survey speed in miles per hour, and outputs off track (left/right), speed, distance to go, and scale information to the front panel displays.

2.2.2 Command Center Data Analysis Software

The Command Center software performs all post processing functions for RADAR survey data. It accepts setup information from the operator and preprocesses data from the survey optical disk. Interactive routines allow an operator to display selected lines of preprocessed data. With data displayed, an operator interactively determines site electromagnetic wave velocity(ies) and logs interactively selected targets. Data processing and image processing routines automatically detect and log targets. Output routines provide traverse and target maps as well as target reports, velocity and site log reports. The interactive routines

also allow an operator to resort the target file with higher detection thresholds without having to reprocess the data.

The RADAR Command Center software is written in the C programming language. The compiled code is stored on the internal hard disk drive. In addition to the main application programs, two support utilities were written to overcome the hardware and operating system limitations. A "RADAR INTER-TASK COMMUNICATION" utility is a multi-tasking system that permits software development by different programmers concurrently and handles the UniFlex task size limit of 256K by allowing RADAR to be broken up into multiple tasks. The second is a memory management utility called the "Heap Manager". This utility provides memory management not provided by the Force CPU-21 or UniFlex. The application program is menu driven; developed detection and processing algorithms are based on adaptations of seismic, machine vision, and in-house expertise. They were initially evaluated and validated with the digital data base of GPR/Ordnance collected at field test sites.

The RADAR processing scheme addresses problems associated with detection of targets in a large area survey and employs a unique approach to automated evaluation of GPR data. The traditional method of GPR data collection involves translating a single GPR transmitter-receiver antenna configuration along the survey line by hand. The resulting analog signal is directed to a magnetic tape recorder or an electrostatic plotter for display and interpretation by visual inspection. Survey speeds must be kept slow to minimize uneven trace spacings that distort the subsurface radar image. The unprocessed data is further complicated by signal ringing and reverberation, reflection from geologic structures and noise. Evaluation of the data through visual inspection therefore requires a skilled interpreter which is both time consuming and expensive.

In order to reduce expense, survey line spacing is typically large which limits the survey resolution. Further, visual inspection of the data is subject to non-uniform interpretation and the introduction of operator bias.

A generalized logic-flow of the processing scheme developed for RADAR is shown in Figure 13. The RADAR processing scheme has three major components: signal processing, image processing, and target identification. Due to the similarity between GPR and seismic data, existing data processing algorithms for enhancing and correctly imaging subsurface seismic data were adapted and applied. Advanced research efforts in machine vision were also adapted for automatic target feature extraction. The unique processing scheme automatically locates subsurface targets in RADAR data.

Data processing begins with a preprocess routine that retrieves survey data from optical disk. GPR data from each antenna are demultiplexed and spatially normalized, using the tick wheel information, to 7.6 cm (3 inch) trace spacing. Figure 14 is an example of normalized data navigation and tick wheel data are stripped and stored in separate files. When preprocessing is completed, a traverse map showing the path that the antenna array traversed during the survey is available for output. This map provides a quick look at the area covered and identifies missed areas that may require additional surveying.

For the first time, range clearance officers can "view" spatially normalized RADAR images that provide detailed, non-destructive information concerning the subsurface character of the survey area. Interactive data analysis routines allow an operator to rapidly identify ordnance/target signatures and geologic structures. Certain targets are selected for GPR velocity

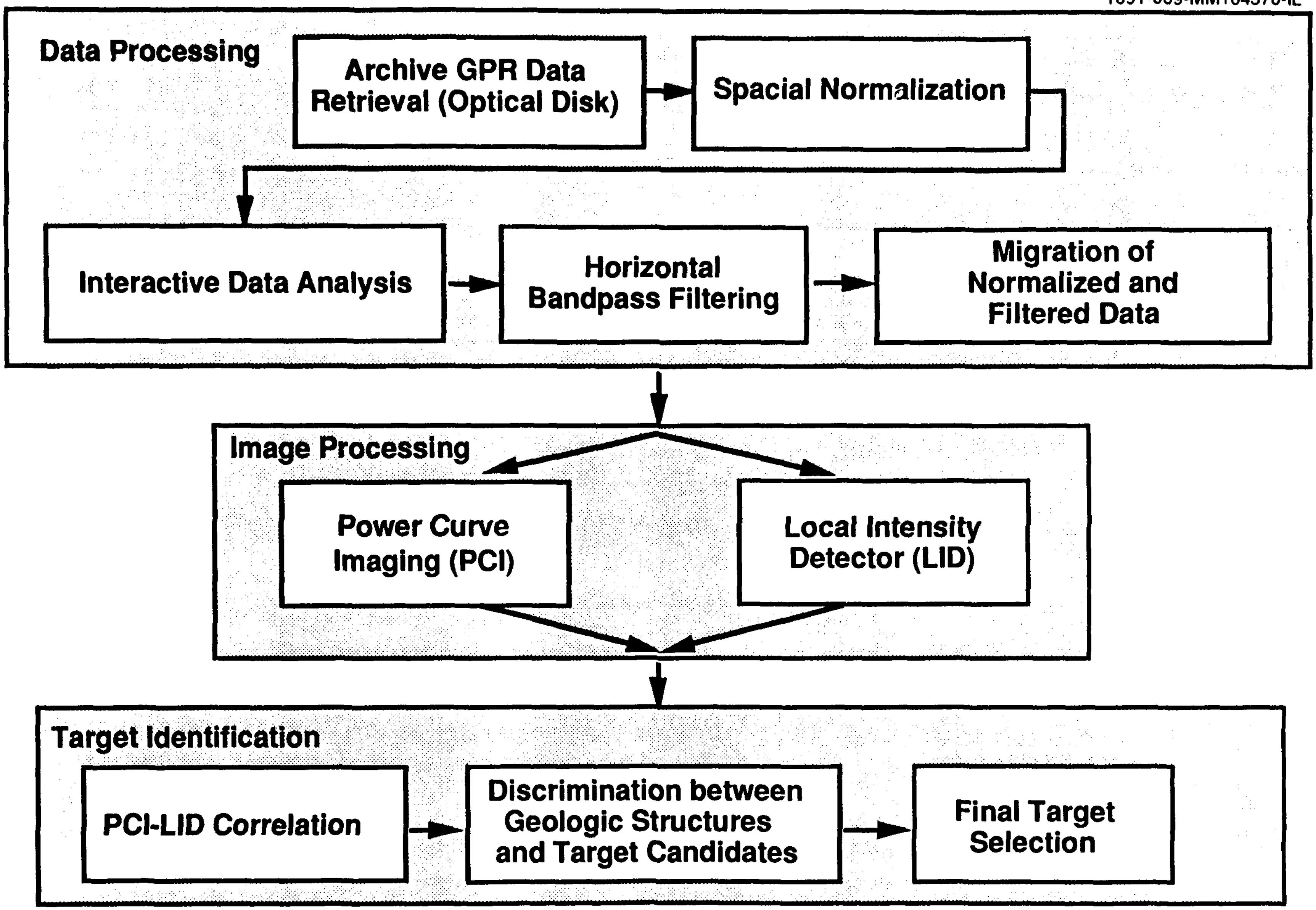

Figure 13.

RADAR Command Center Processing Scheme

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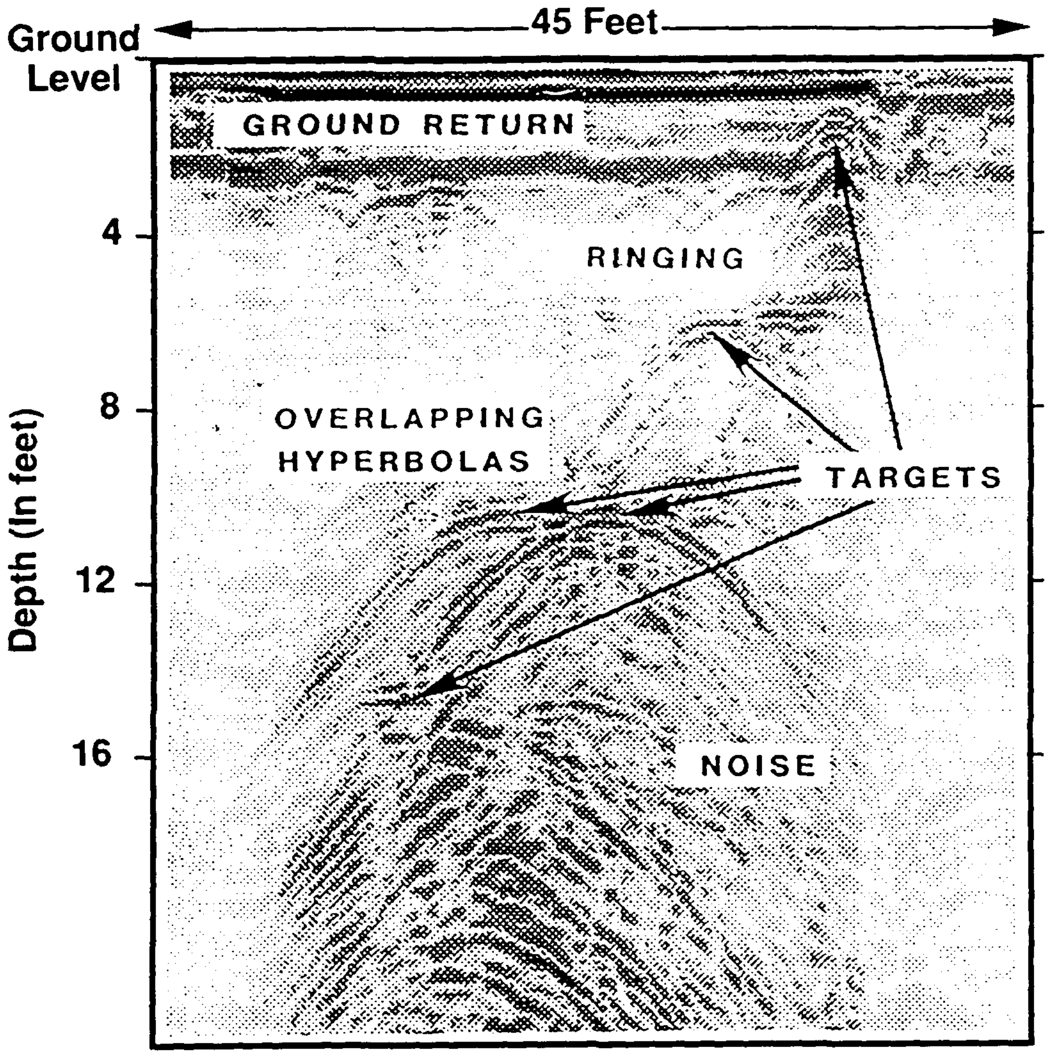

Figure 14.

Digitized GPR Data After Normalization

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analysis. Accurate knowledge of this variable is required for data processing and target depth determination. By matching a computer generated hyperbola to the normalized target signature, the GPR velocity for that part of the survey area is uniquely determined. This is discussed in depth in Appendix A. This procedure effectively calibrates for local geological conditions. The operator can also interactively select targets for "same day" output. Upon completion of the interactive portion of data processing, an interactively selected target map, its associated target report, and the site velocity report are available for output.

Data processing continues with the application of a horizontal filter. The normalized GPR data is filtered to remove the horizontal banding which dominates the GPR profile. Viewed in the direction of antenna translation, the banding is of low frequency components that, in theory, can be removed by applying a simple highpass filter. However, the filtering is complicated by a number of factors. The earth preferentially attenuates the high frequency components of the radar pulse with increasing depth which caused a corresponding variation in frequency character of the data. This requires that the filter passband be shifted to a progressively lower center frequency with increasing depth in the GPR profile. The filtering is further complicated by the necessity to filter the data in the time domain. The large size of a typical GPR data set makes transformation of the data to the frequency domain impractical.

The filtering is achieved through the use of a time-domain recursive bandpass filter. A published algorithm is used to calculate the filter weights given the 3 dB down points of the frequency passband (Nikolic, 1975) [1]. The passband variation

with depth is achieved by recalculating new filter weights at each sample depth in the radar image. Figure 15 shows the filter passband at several sample depths, grading from a highpass to a lowpass with depth. The most effective filter for the GPR data collected in this study graded from a highpass to a lowpass in an exponential manner with depth.

Normalized and filtered data collected at NAVEODTECHCEN is shown in Figure 16. The filtering has effectively removed the horizontal banding which dominated the normalized data while preserving the character of the hyperbolic returns from the targets.

A migration algorithm then operates on the data to increase the target signal to noise ratio and to focus the GPR energy from subsurface targets. Migration is a method of processing radar data which images reflectors at their true locations in the ground. During data collection, the radar antenna imparts a radially propagating wavefront into the earth. For a point target in the subsurface, the returning energy is dispersed along a characteristic hyperbolic curve. The shape of the hyperbola is determined both by the depth to the target and the electromagnetic wave propagation velocity profile in the earth. Figure 17 illustrates how the hyperbolic curve is produced by a point reflector in the subsurface. The return time of the energy reflected from a target is dependent on the horizontal position of the antenna relative to the center of the target. The lower half of Figure 17 illustrates how the return times map out a hyperbolic pattern as the antenna passes over the target. Determination of the curve shape can be made given the antenna traverse path along the ground and the electromagnetic propagation velocity in the earth. For a target acting as a localized scatterer in the

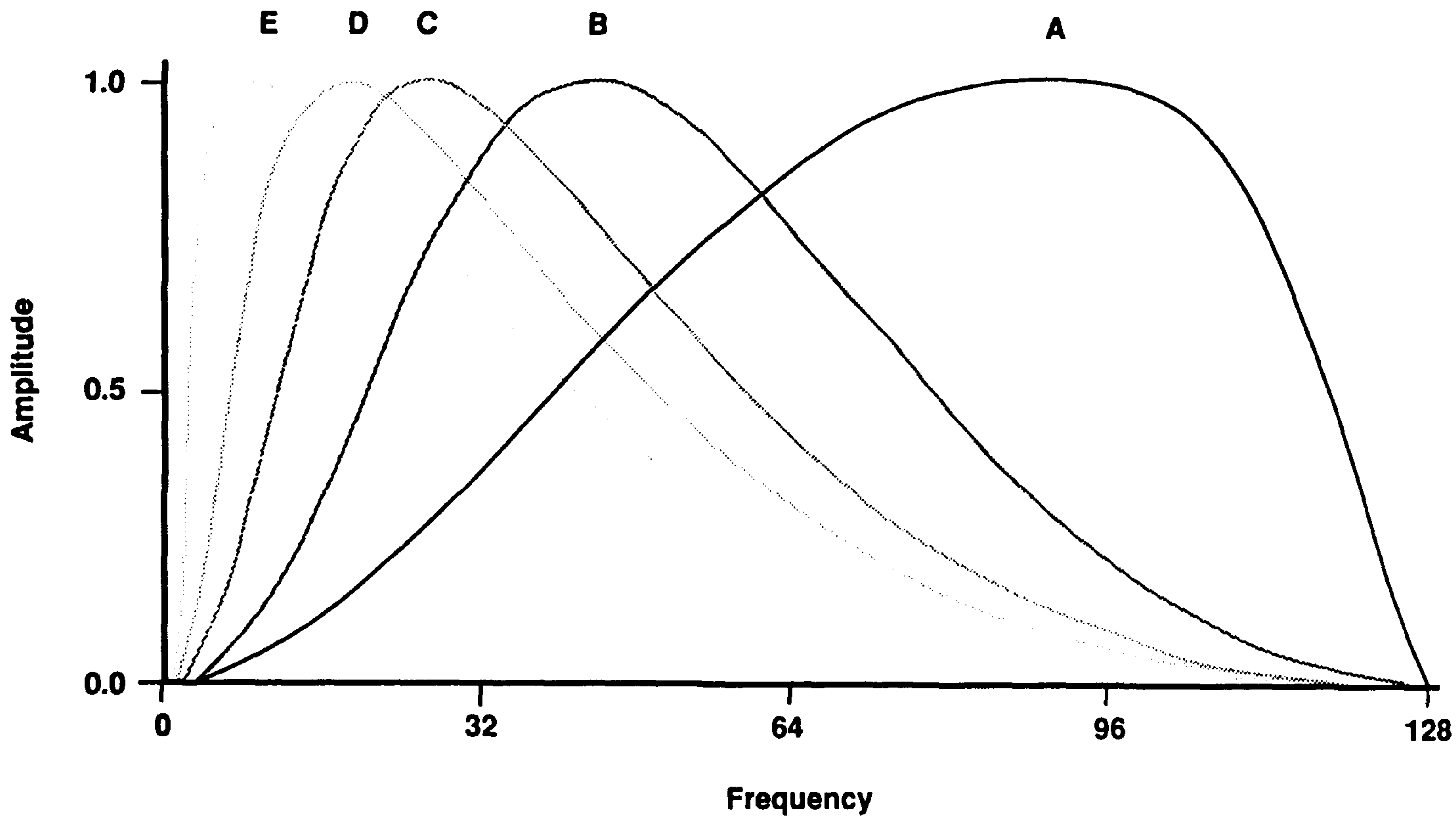

Figure 15.

Filter Pass Band at Various Depths Grading from High Pass to Low Pass

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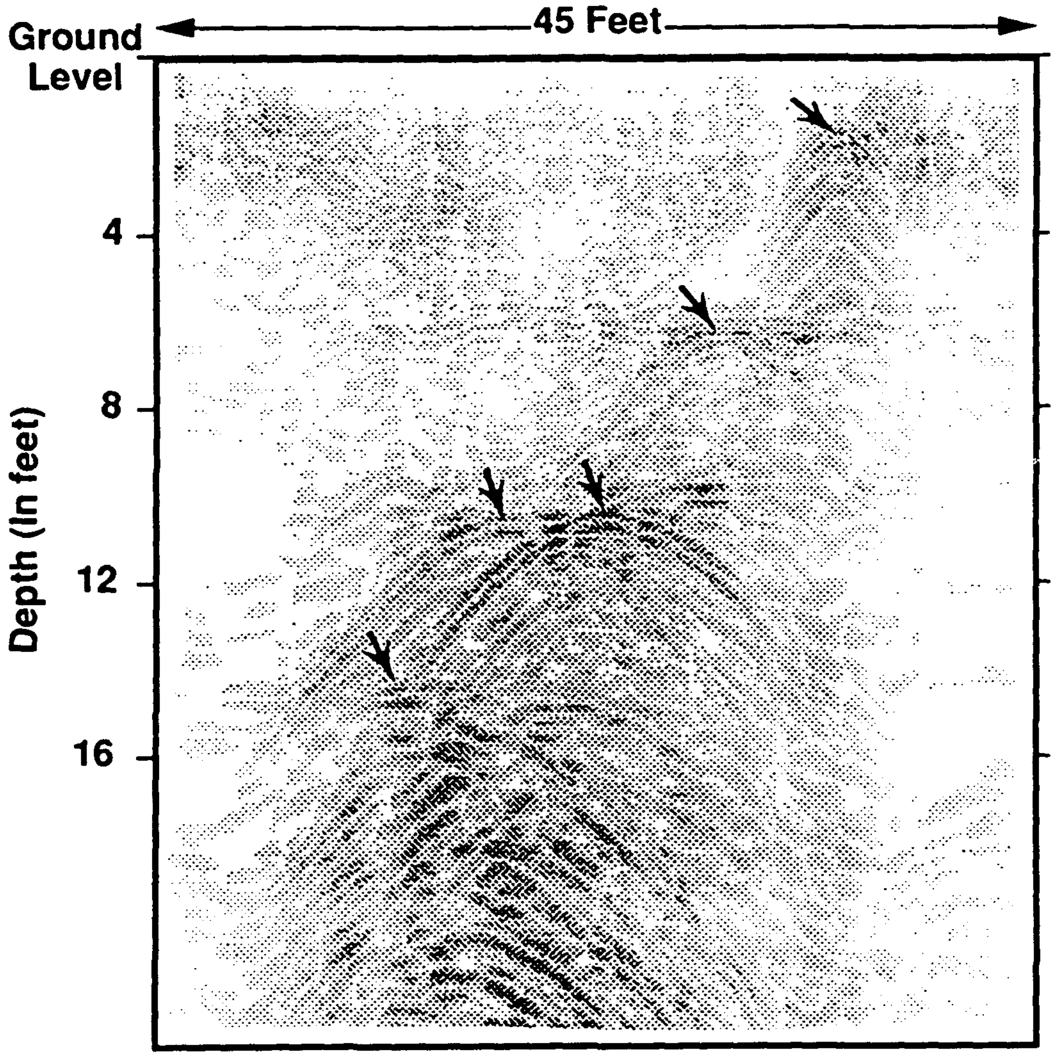

Figure 16.

Normalized and Filtered GPR Data Showing Results of Background Reduction

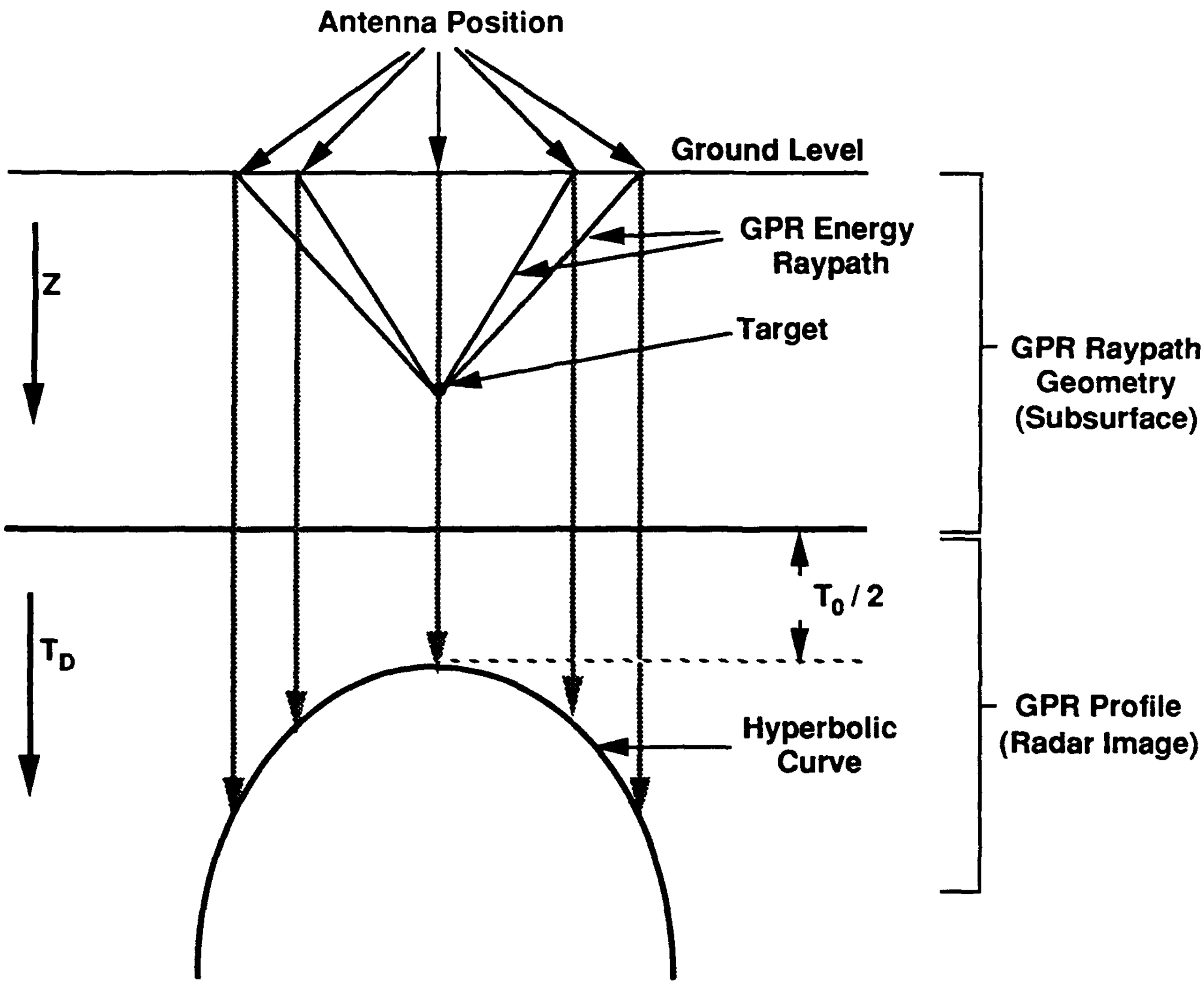

Figure 17.

GPR Return Energy from a Point Target

subsurface, the returning GPR energy is dispersed along a characteristic hyperbolic curve centered on the target. Target detection is predicated on correctly locating the apex of this hyperbolic curve.

There are several problems associated with locating targets in the unmigrated GPR data. Most of the energy from the target is not mapped at the actual target location but is distributed across the radar section along the hyperbolic curve. Since only a small amount of the initial pulsed energy strikes the target and an even smaller amount is actually detected, the signal to noise ratio on any given trace (on any given point along the hyperbola) can be quite small (close to one). Further, targets which are in close proximity to each other produce overlapping hyperbolic curves making individual target recognition difficult.

The migration process integrates the energy values over the hyperbolic curve and focuses the resultant sum at the apex of the curve, greatly enhancing target detectability. The migration algorithm used in this study is based on the Kirchoff migration theory discussed in Appendix B. This involves integrating the energy values over the characteristic hyperbolic curve and the focusing of the resultant sum at the apex of the curve. The migration process correctly positions subsurface reflectors, improves the signal-to-noise ratio, and facilitates target detection and location. In practice, migration processing is conducted for all points in the data set since the target locations are not known. A summation is preformed along the calculated hyperbolic curve for each point in the data set. If the apex of the curve does not lie on a target, then the radar energy samples in the migration integral, consist of random noise signals which sum to a statistically small amplitude. In contrast, if the

migration integral is computed over a hyperbolic target signature, then the radar energy signals are correlated and the summation produces a large amplitude result.

Figure 18 shows the results of migrating the normalized and filtered data. Much of the incoherent noise present in the normalized and filtered data has been eliminated and almost all the targets appear as small but intense amplitude anomalies which can be readily located through the application of image processing techniques.

Targets in a normalized, filtered and migrated radar image are characterized by local high amplitude anomalies which can be identified and located through the application of image processing techniques. Two image processing algorithms, coined "Local Intensity Determination" (LID) and "Power Curve Imaging" (PCI) are applied independently to the radar image. Final target candidates are located through correlation of the target candidates identified by the two algorithms.

Local Intensity Determination (LID) is an image processing technique which enhances local amplitude variations in the radar image. Because targets are associated with focused high-amplitude anomalies, target candidates in the radar image can be easily located after the application of the LID algorithm. Figure 19 illustrates the geometry involved in the transformation procedure. Two concentric boxes with dimensions m x n (inner box) and j x k (outer box) are centered at x_0, z_0 in the radar image where m and n are multiples of j and k respectively. The difference between the mean intensities of two boxes is calculated and is mapped to point x_0, z_0 in the difference map. The transformation function is effectively a highpass filter which enhances amplitude anomalies

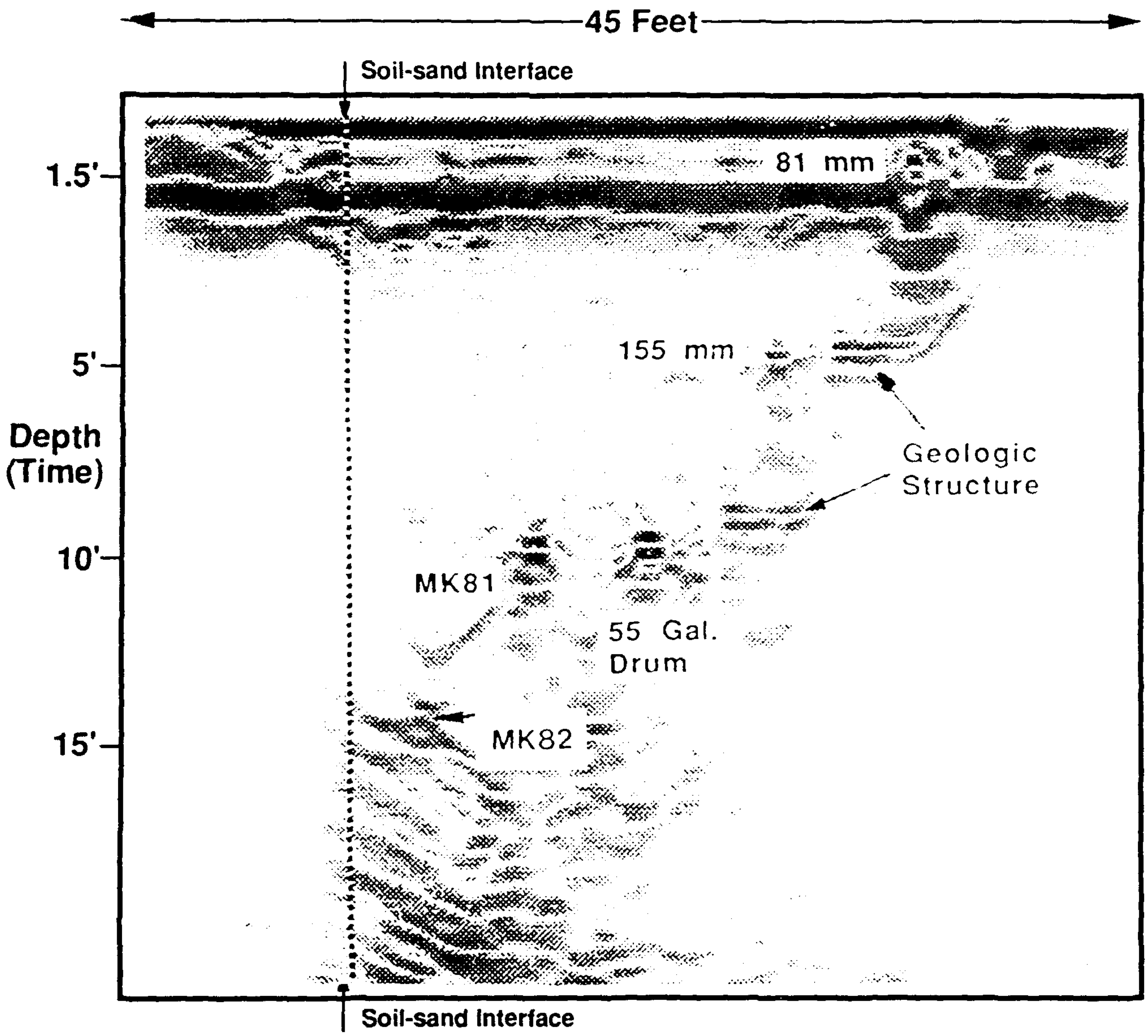

Figure 18.

Migrated Data Based on Kirchoff Theory

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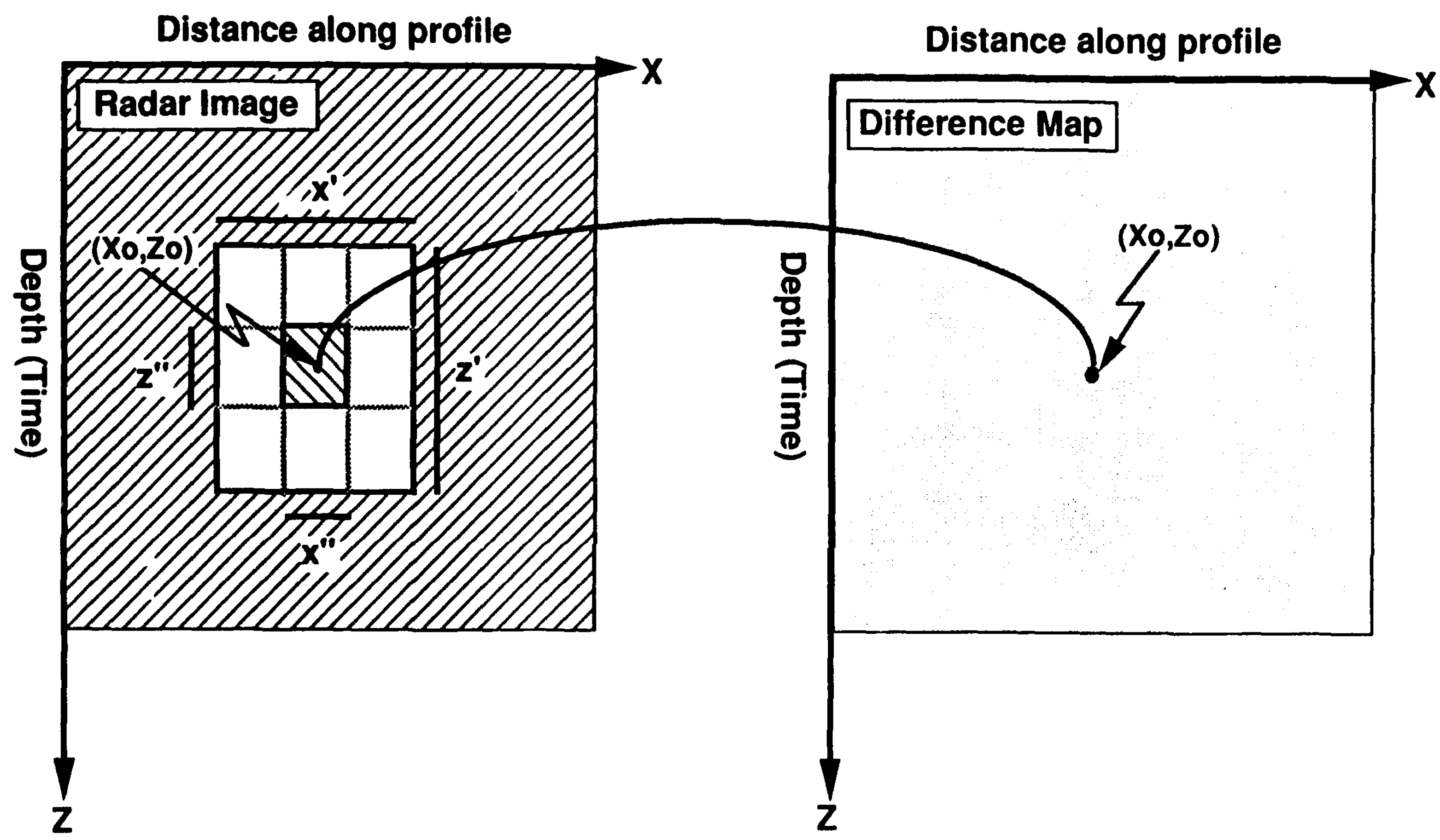

Figure 19.

Local Intensity Determination (LID) Image Transformation Geometry for Enhancement of Local Amplitude Variations in Radar Images

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with dimensions near those of the inner box, since the difference in the mean of the two boxes is small for both large anomalies and noise. The concentric boxes are translated to an adjacent sample location and the procedure is repeated until a difference value is calculated for every location in the data set. LID creates a difference map of the radar image in which amplitude anomalies are enhanced.

Power Curve Imaging (PCI) is used to locate areas of the radar image with amplitude values that exceed the regional noise level. PCI calculates the power (squared amplitudes) in each trace by vertically summing over a specified number of samples:

$$A(T) = \sum_{s=1}^{N_T} B(s,T)^2$$

Where s = The current sample in trace T.

$A(T)$ = PCI sum for trace T.

N_T = Number of samples in trace T used in PCI calculation.

$B(s,T)$ = The sample intensity at location (s,T).

Since PCI highlights regional trends in intensity variation, care must be taken in applying the algorithm after horizontal filtering. The marked variation in the background intensity level with depth due to the filtering requires PCI to be performed independently over three overlapping sections of the data set. These sections are referred to as "sample bands", and correspond to shallow, intermediate, and deep sections of the radar image. In Figure 20, PCI was applied to the shallow sample band of the radar data. The target located in the upper right-hand corner of the image stands out as a sharp spike in the PCI plot.

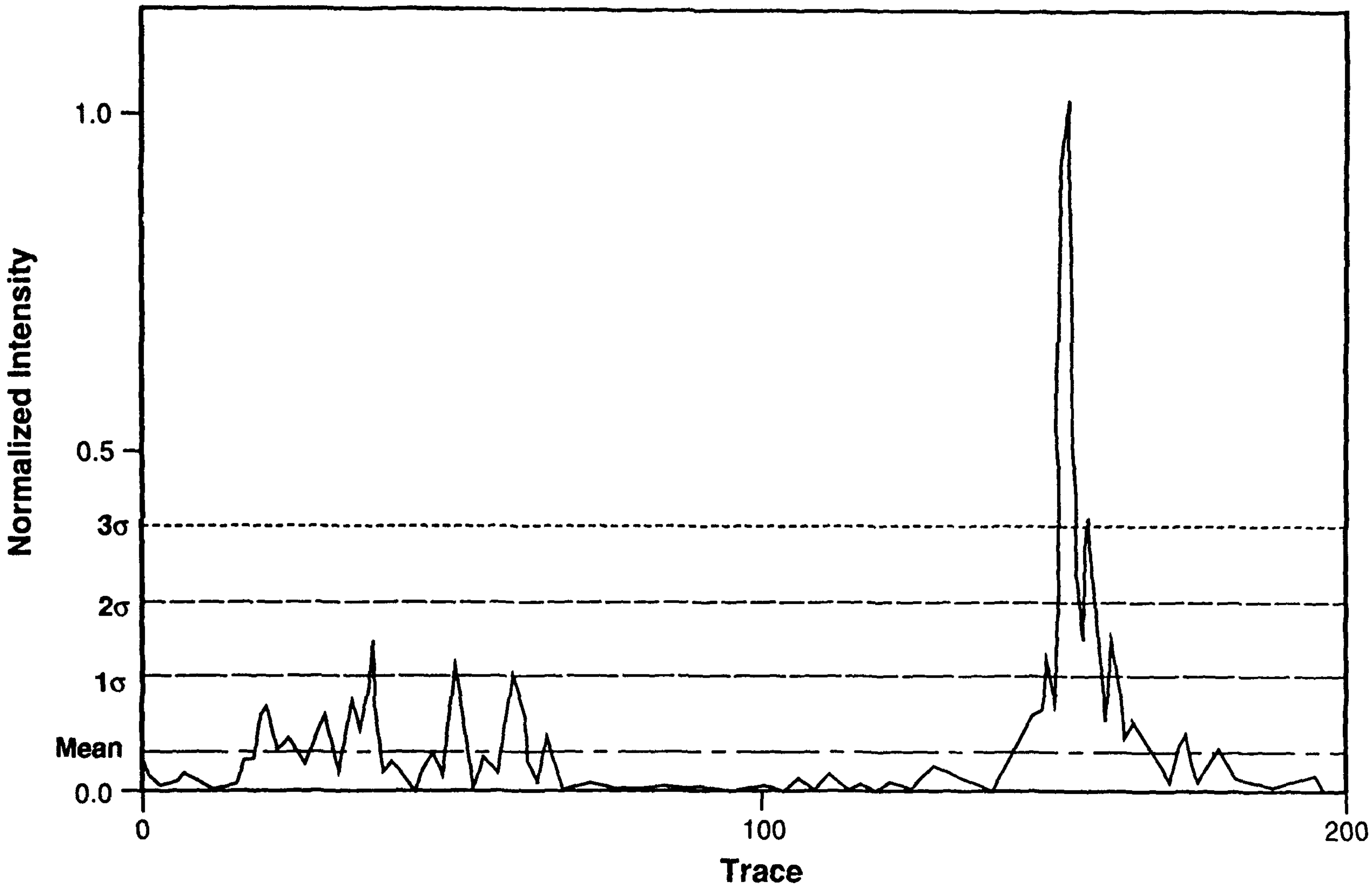

Figure 20.

Power Curve Image (PCI) Example of Radar Data Showing a Target as a Sharp Spike Separating It from Noise

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The principal reason for applying PCI to the image file is to reduce the number of target identifications due to noise. Although LID identifies local regions of high amplitude contrast in the radar image, such regions are not necessarily associated with actual targets. Often there are amplitude variations associated with noise which are as prominent as those from a target. PCI delineates amplitude anomalies in the radar image which have significant vertical extent. Shallow target features can include signal ringing or "shadow zones" beneath the target hyperbola in the radar image. Shadow zones are regions of very low signal amplitude directly below the target image. This phenomenon is caused by the radar energy being blocked from deeper penetration by the target. After migration processing signal ringing is partially focused giving rise to a large PCI value in the target trace. In the case of shadow zones, migration tends to "fill" the low amplitude area below the target with surrounding higher amplitude data. This artifact of the migration process results in a vertical extension of the amplitude anomaly associated with target. Noise, on the other hand, lacks this vertical continuity. PCI is, therefore, very effective in reducing the number of target identifications due to noise.

Selection of the final target candidates in the radar image is based on a correlation between candidates identified in the LID and PCI algorithms. The correlation algorithm compares the overlap of PCI and LID target candidates after the application of a threshold to both data sets. The threshold values are based on and expressed as a number of standard deviations above the mean of the data set.

In PCI, a threshold is applied to each sample band to identify PCI target candidate A 5-trace window is constructed about the trace associated with the target candidate which exceeds the

threshold. In LID, local high amplitude anomalies (target candidates) are also identified through the application of a threshold. The thresholding yields the coordinates (x_i, z_i) of the LID target candidates. Final target candidates are defined to be those target candidates in LID which fall within the windows about the PCI target candidates. The correlation is carried out independently over each of the sample bands in the radar image.

The final step in the processing scheme is the elimination of final target candidates which are due to geologic features. There exist many high-amplitude features in the radar image which are associated with geologic features such as the water table and soil interfaces. Target candidates associated with these features tend to form lenticular clusters with a horizontal orientation, whereas target candidates associated with actual targets form clusters which are horizontally short and are often vertically elongated due to ringing and shadow zone effects. A least-squares fit is performed to determine the trend and the coherence of clusters formed by target candidates. Clusters which have a large correlation, (indicative of a strongly lenticular group), and trend with a shallow slope, are considered to be associated with geologic features and are eliminated from the final target list. Figure 21 shows the target candidates before and after the application of geologic discrimination. Clearly, all the real ordnance targets in the sample have been identified. An extra target, directly below the shallow target, which is the sand/native soil interface has also been identified. This geologic feature with a lenticular appearance and a very shallow slope is eliminated after the application of geology discrimination as can be seen in the second part of Figure 21.

The output routines provide all system reports and maps. Outputs available include:

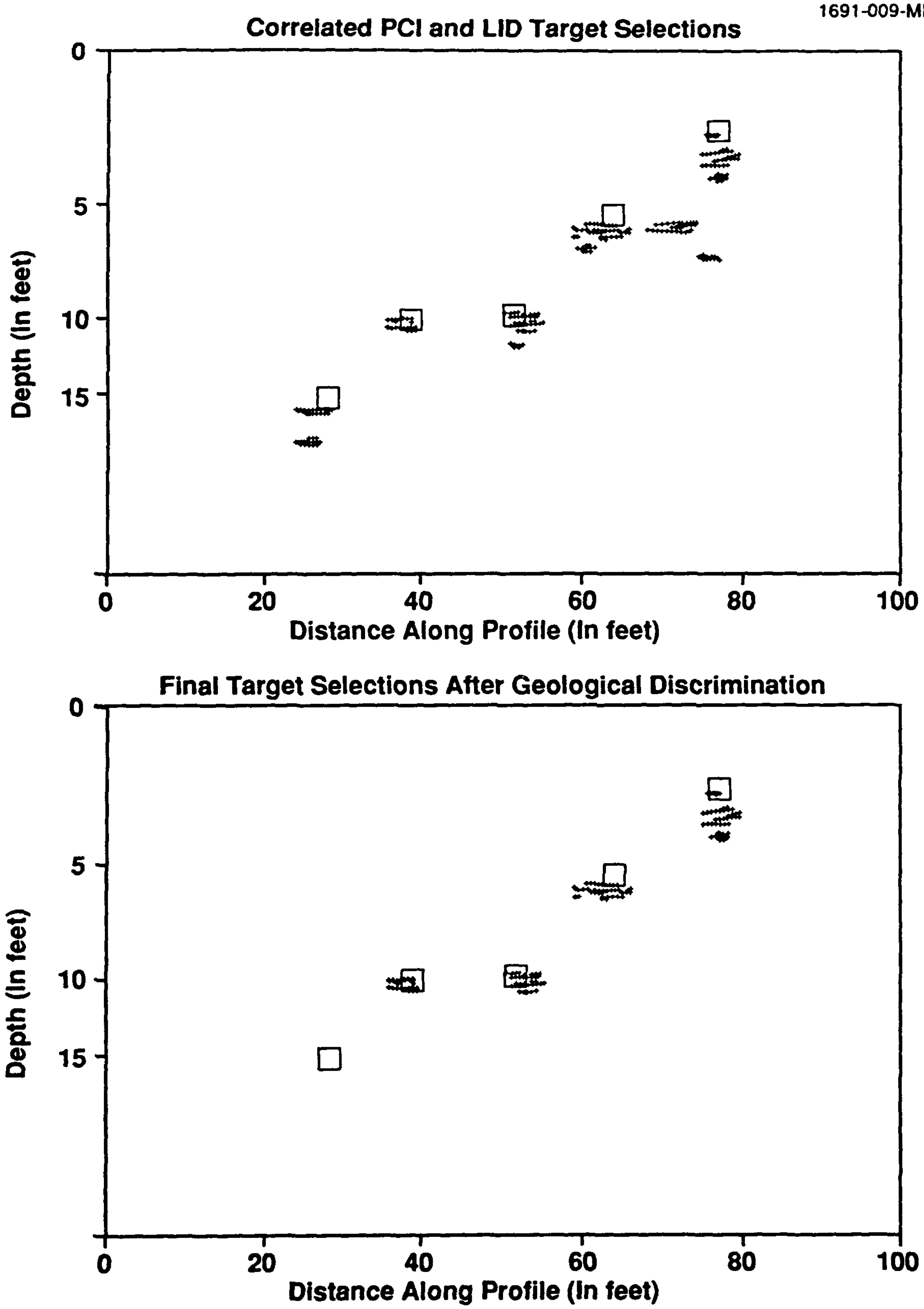

Figure 21.

Target Selections Post PCI, LID and Geological Discrimination

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- Traverse Map - shows site coverage and missed areas
- Target Report - printout of target number, (x, y, z) location, and method of selection (v = velocity or interactively selected; a = automatic)
- Target Map - plot of targets over traverse map
- Velocity Report - printout of velocity values determined over survey area
- Site Log - printout of operator selected keystrokes - useful for analyzing analysis techniques or reprocessing data with the same operator selected variables
- Optical Disk Directory - provides a printout of files on the optical disk which match the selected site identification code

Detailed operator instructions are provided in the Operator's Manual. Example RADAR Target Report and Target Map are shown in Figures 22 and 23.

3.0 SYSTEM PERFORMANCE

3.1 Field Test and System Debug

Acceptance tests were performed at the 6A site at Fort Devens, Massachusetts in October 1989. The prepared area covers approximately two acres, within which are buried eight ordnance items and 26 ordnance simulants. Simulants were emplaced specifically for field tests of the Ground Penetrating Radar Ordnance Search System. The remote navigation stations (RNS) were located along the perimeter of the site and their coordinates were surveyed with the navigation calibration procedure. Soil conditions are classified as unconsolidated glacial till consisting of many layers of sand and gravel wash from a neighboring hillside.

Field operations began with setting up the RNS at four locations around the survey area. The RADAR Tow Vehicle (RTV) was

29 Palms Test Range TARGET REPORT Mon., May 21, 1990

Site ID: TPT2

LINE	X	Y	DEPTH	METHOD
0008P	1114.5	1057.1	0.401	V
0018C	1091.8	1062.3	1.265	V
0021C	1083.9	1120.0	1.111	V
0022A	1076.6	975.8	2.283	V
0022C	1079.3	1119.6	0.771	V
0023C	1077.2	1063.8	0.895	V
0035A	1042.1	997.3	1.543	V
0035B	1042.9	997.2	1.234	V
0040C	1032.5	1016.5	0.895	V
0047A	1019.7	1072.4	0.864	V
0048C	1008.7	1092.9	0.987	V
0049B	1020.8	1073.5	0.679	V
0060C	1084.6	993.9	1.111	V
0060C	1084.2	997.6	1.141	V
0001D	1135.0	974.6	0.586	V
0001D	1139.4	113.2	0.463	V
0002A	1131.0	989.1	0.987	V
0005A	1120.5	970.6	1.141	V
0006B	1119.1	969.7	0.771	V
0007B	1122.5	1151.6	0.463	V
0025D	1069.8	982.8	1.080	V
0026A	1069.1	1036.4	1.141	V
0027A	1068.7	1037.8	0.956	V
0027B	1070.2	110.4	0.864	V
0027C	1069.5	1099.9	0.802	V
0030C	1055.8	1014.1	0.864	V
0042C	1030.4	1114.2	0.524	V
0043C	1026.0	1105.6	0.710	V
0045A	1022.5	1092.5	0.648	V
0045A	1020.3	1073.0	0.679	V
0046C	1021.1	1070.4	0.864	V
0055A	1008.9	1130.4	0.833	V

VISUALLY PICKED TARGETS FROM 29 PALMS SURVEY

Figure 22.

RADAR Target Report

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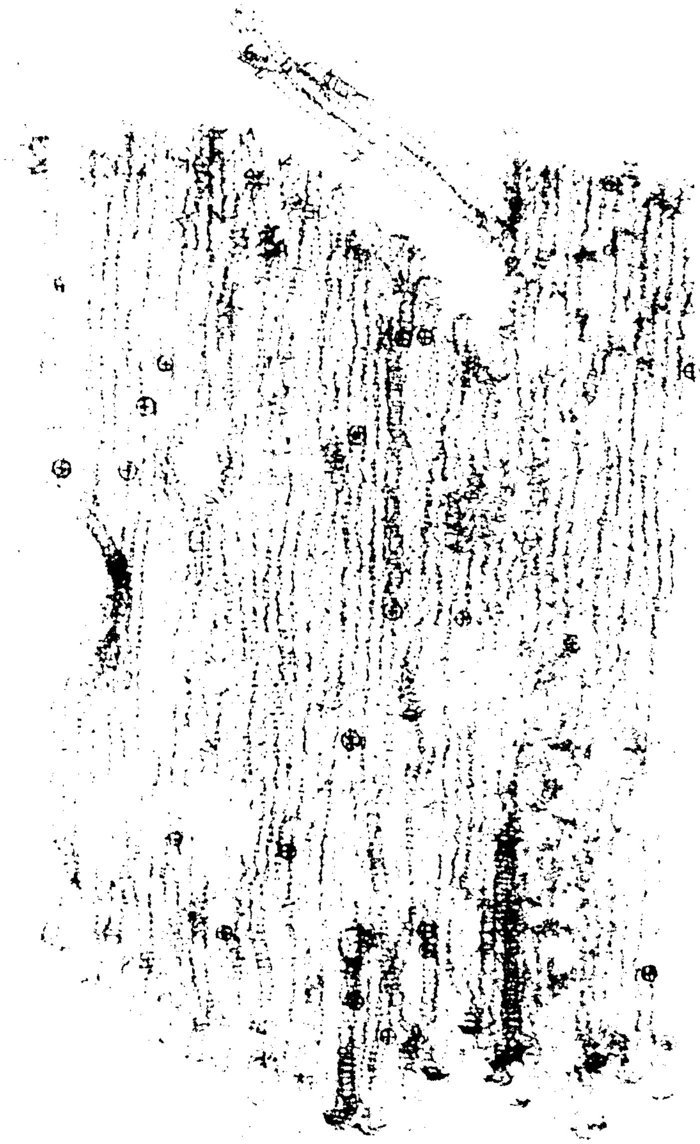

Figure 23.

RADAR Target Map

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prepared for data acquisition. The RADAR Tow Platform (RTP) was assembled and prepared for a field survey. For the purposes of the acceptance tests, the RADAR Command Center (RCC) remained at GEO-CENTERS' facilities. Acquired GPR field data were transferred to the Force computer in the RCC, on optical disk and processed to generate reports and maps. The Fort Devens acceptance test data processed as designed. The automatic target selections were complimented by interactive target selection and a target map and target list were produced. Thirty-three of the thirty-four targets (97%) were successfully detected and located. All 500 pound bomb targets buried from 15 cm (6 inches) to 4.5 meters (15 feet), all 250 pound bomb targets buried from 15 cm (6 inches) to 3 meters (10 feet) and all but one 155 mm targets buried 15 cm (6 inches) to 1.5 meters (5 feet) were detected and located. The one missed target was a 155 mm projectile, 3 feet deep, oriented nose up. The layered geology and a shallow (15-20 foot) water table were sources of false alarms. Most of these false alarms were subsequently screened by operators interactively reviewing the processed results.

Based on these test results, RADAR was delivered to the Naval EOD Technology Center, Indian Head, Maryland in October 1989. The Operators' Manuals, Volumes I and II were updated and a set of operation checklists were generated to insure proper set-up and take down procedures are followed.

Arrangements between NAVEODTECHCEN and the EOD detachment at the Marine Corps Air Ground Combat Center in Twentynine Palms, CA, led to the establishment of a blind test site for RADAR evaluation. The quantity, location and identity of targets within the site were known only to Navy representatives. The site comprises approximately seven acres of desert hillside terrain, and is fenced

in with barbed wire. Sparse vegetation made the site accessible, except in arroyo areas, around large shrubs and mounds of excavated earth. Soil conditions are classified as high desert sand with a high rate of colluvial deposition from surrounding hills. The soil is highly mineralized.

Comprehensive tests occurred during April 1990. For each test, the four RNS were mounted on pre-established posts on the perimeter of the survey area. The RCC was stationed inside the EOD compound, where AC line power was available for the computer and terminal. One generator was used to supply unregulated power. Multiple data sets were acquired. The data were transferred to the RCC computer and processed. Analyzed GPR field data provided coordinates for target relocation using the waypoint guidance capability of the navigation system. The Tow Vehicle and Platform operated successfully over the test range terrain for four consecutive days. One complete range survey and twelve separate surveys of different portions of the ordnance test range were acquired. The Command Center operated the entire time and successfully processed selected survey data.

Calibration of the GPR over a calibration target buried 0.75 m (2.5 ft.), showed a high electromagnetic wave velocity of 2.45 x 10E8 m through the soil. This velocity was calculated by knowing the time delay between samples, and the two way travel time to the calibration target. The velocity value was verified in the Command Center during Interactive Velocity Analysis described previously. With this high velocity value, expectations were that system design objectives for detection would be exceeded. However, it was also noted during the radar calibration procedure, that very large, exponential range gain values would not saturate late (deep) signals as expected. This indicates that the local soil structure

attenuates the signal severely yielding poor deep target detection results. Evaluation tests were then structured to acquire data in different areas over targets at a range of burial depths to empirically determine RADAR's detection capability in this soil.

The data from the complete range survey, "TPT2", was preprocessed and a traverse map was plotted. Data from an area containing shallow buried targets, "TPTB", was processed both automatically and interactively. All of the targets in that area were reported to be found using both interactive and automatic techniques. Targets maps were plotted and target reports were printed for both the automatic and interactive target processing techniques. Initial results of data processing from other limited area surveys containing deep targets indicates that due to geological constraints, targets deeper than 5 feet are not detectable.

Data from the full area survey were interactively processed and data from one small survey identified as having a range of shallow buried targets was processed both automatically and interactively. The deepest target (B7, a MK 81 bomb) was detected and located at a 4.7 foot depth. Between the two data sets processed, a total of fourteen targets were accurately located. Four of these targets were smaller than 155 mm projectiles. Discounting targets deeper than 5.0 feet due to geological constraints and those ordnance targets smaller than 155 mm projectiles due to GPR (300 MHz) resolution constraints, ten out of twelve (83%) targets were detected. The two undetected targets were D1 (a 155 mm projectile, 4.0 feet deep, 67° nose down) and D2 (a 155 mm projectile, 5.1 feet deep, 247° nose up).

Radar field exercises were performed at Indian Head, MD in March 1990. The Stump Neck Road test site is located at the Naval

Explosive Ordnance Disposal Technology Center (NAVEODTECHCEN). The site is a former wooded area that has been cleared and graded. A 100 by 200 foot section of the area, designated the Magnetic Test Range (MTR), contains 14 carefully emplaced ordnance items, ranging from 60 mm projectiles to 500 lb bombs (MK82) designed primarily for evaluation testing of magnetometer search systems. The local soil is silty clay. Locations for the four remote navigation stations were surveyed and flagged. The RTP, RTV, and RNS were all prepared and operated in accordance with the procedures in the Operator's Manual.

MTR survey data was transferred to the RCC computer and was preprocessed and interactively processed. Target pick results indicate that only one of the fourteen test targets was successfully detected. Due to the fact that the survey grid did not correspond to the MTR reference grid and insufficient orientation data was recorded, target location verification was not absolute. Designed to detect and locate 155 mm projectiles and larger ordnance, only six test targets were within RADAR's target resolution. The clay geology restricted GPR penetration to less than ten feet obscuring four of the six targets. The last target, a 155 mm projectile buried five feet deep, oriented nose up was not detected.

4.0 CONCLUSIONS

The development, test and evaluation of RADAR has proven that the developed system operates extremely well and large areas, contaminated with ordnance items can indeed be surveyed quickly and accurately. For the first time, range clearance officers can "view" spatially corrected (normalized) RADAR images that provide detailed, non-destructive information concerning the subsurface character of the survey site. Targets are located to within +/- 1

meter of their actual location, and permanent records, both reports and maps, are automatically generated, detailing site survey and clearance activities. The concept of a Ground Penetrating Radar (GPR) Ordnance Search System based on a four wheel drive vehicle towing an array of GPR antennas is sound. The RADAR Tow Vehicle is well suited to the task.

The 286 PC-based Operator Control and Display Computer (OCDC) worked without incident. For proof of principle, the data acquisition controller was limited to a single CPU. The 286 CPU should be upgraded to a 386/486 board with potential expansion for a support processor to improve storage and real time display operations. The RADSIB board design should also be upgraded to permit multiple DMA data transfers (i.e., from the Radar Controller and to the Optical Disk).

The Radar Controller also worked well. While all wire wrapped circuit boards performed without incident, conversion to printed circuit boards would insure higher reliability now that proper functioning has been confirmed. Brighter LED's should be used on the front panel.

The Racal navigation control/measurement unit (CMU) performed satisfactorily. All socketed components and jumpers have been secured to assure against vibration induced disconnection.

The Audio Link in the tow vehicle and Command Center operated as designed but proved to be of little utility. Radio links at Twentynine Palms, CA were provided by military radios whose operating frequencies matched base networks. Future operations should consider integrating and using radios supplied by the local base of operations.

The Tow Platform proved to be adequate for controlled, proof-of-principle tests. A major strength of the tow platform is its ease of deployment. The GPR antenna suspension method allows antennas to float over local terrain in the vertical plane.

All system cable assemblies proved to be adequate for this stage of design. In general, all cable assemblies should be upgraded to include Mil-Spec shells with crimp pins and environmentally sealed backings.

The four RNS serve their purpose. All T/R units have been retrofitted with flexible coax from the antenna to the internal card cage as a defense against vibration induced breakage.

The Command Center performed as designed. It provided a balanced environment, that insured proper equipment operation. The enclosure provided sufficient workspace in which to perform any required repairs. The computer and peripherals all performed as designed. The computer should be upgraded to a CPU-32 processor with on-board memory management.

RADAR software in both the tow vehicle and command center proved to be robust and adequate for this demonstration prototype.

The Operator Control and Display Computer (OCDC) software performed without incident during evaluation testing. The program is currently stored on hard disk, and requires the use of a monitor to boot the application program. Porting the executable code to electrically programmable read only memory (EPROM) would eliminate the need for both the hard disk drive and the development monitor. The OCDC program is written in Microsoft assembly language.

The Track Guidance software performed as designed. No problems were encountered and no upgrades are proposed.

The Command Center software performed as planned. The data processing scheme provides an efficient and effective means for processing the large amounts of data collected during a large area GPR survey. The scheme has been used to successfully locate buried ordnance targets. The individual algorithms which include normalization, horizontal bandpass filtering, migration, image processing (LID and PCI), and geologic feature discrimination have been designed to locate targets of small spatial extent but could be modified to detect larger targets or particular geologic structures for a wide variety of applications. Additional algorithm evaluation is required to optimize site dependent and adjustable variables. Post processing execution time can be significantly improved.

Overall, Radar performed its specified functions. In terms of deployable hardware, RADAR is well suited for proof-of-principle demonstration and test. It does locate ordnance of the size and at the depths for which it was designed. It's success rate is however dependent on soil conditions which may be intrinsically hostile to electromagnetic signal propagation. Two of the test sites contained geological conditions which were of this nature. They were the California high desert conditions where the soil is sand with a high rate of mineralized colluvial fill and Maryland's silty clay. In the Massachusetts test site, where the soil was unconsolidated glacial till with many layers of sand and gravel, the system had a 97% location success rate. The system and technology has wide application to ordnance location as well as to other environmental pollution problems. It provides the ability to survey and document results in the most cost effective manner available today.

REFERENCES

1. Nikolic, N.J., 1975, "A Recursive Time-Varying Band-Pass Filter", Geophysics, 40, 520-526.

APPENDIX A
INTERACTIVE VELOCITY DETERMINATION OF THE GPR MIGRATION VELOCITY

In a GPR survey a radar transmitting and receiving antenna configuration is translated along a straight line across the ground. For a point target in the subsurface, the returning energy is dispersed along a characteristic hyperbolic curve as shown in Figure A-1. The shape of the hyperbola is determined both by the depth to the target and the electromagnetic propagation velocity in the earth.

The processing technique, migration, integrates the energy values over the hyperbolic curve and focuses the resultant sum at the apex of the curve, greatly increasing target detectability. Migration requires that the electromagnetic propagation velocity in the earth be known. The earth velocity is calculated in the Interactive Velocity Analysis module by matching an overlaid hyperbola with a real, spatially normalized, target hyperbola. The process is detailed below:

The general form of a hyperbola is:

$$(y-k)^2/a^2 - (x-h)^2/b^2 = 1 \qquad (1)$$

The parameters k and h are measures of the displacement of the hyperbola focus point from the zero of the coordinate system, as shown in Figure A-2.

For convenience, let us move the coordinate system so that it is aligned with the hyperbola center and coincident with the ground surface. In this case, k=h=0 and the general form reduces to:

$$y/a^2 - x^2/b^2 = 1 \qquad (2)$$

The asymptotic slope, S = a/b, is the slope that the tails of the hyperbola reach in the limit of infinite extent, and is a measure of the hyperbola "wideness" or "narrowness", as shown in Figure A-3. It so happens that the electromagnetic propagation velocity, V, is simply the reciprocal of the asymptotic slope, mainly:

$$S = a/b \qquad (3)$$
$$V = 1/S \qquad (4)$$

Using equations 3 and 4, equation 2 can be rearranged:

$$y^2 = a^2 + x^2a^2/b^2 = a^2 + x^2/V^2$$
$$y = (a^2 = x^2/V^2)^{1/2} \qquad (5)$$

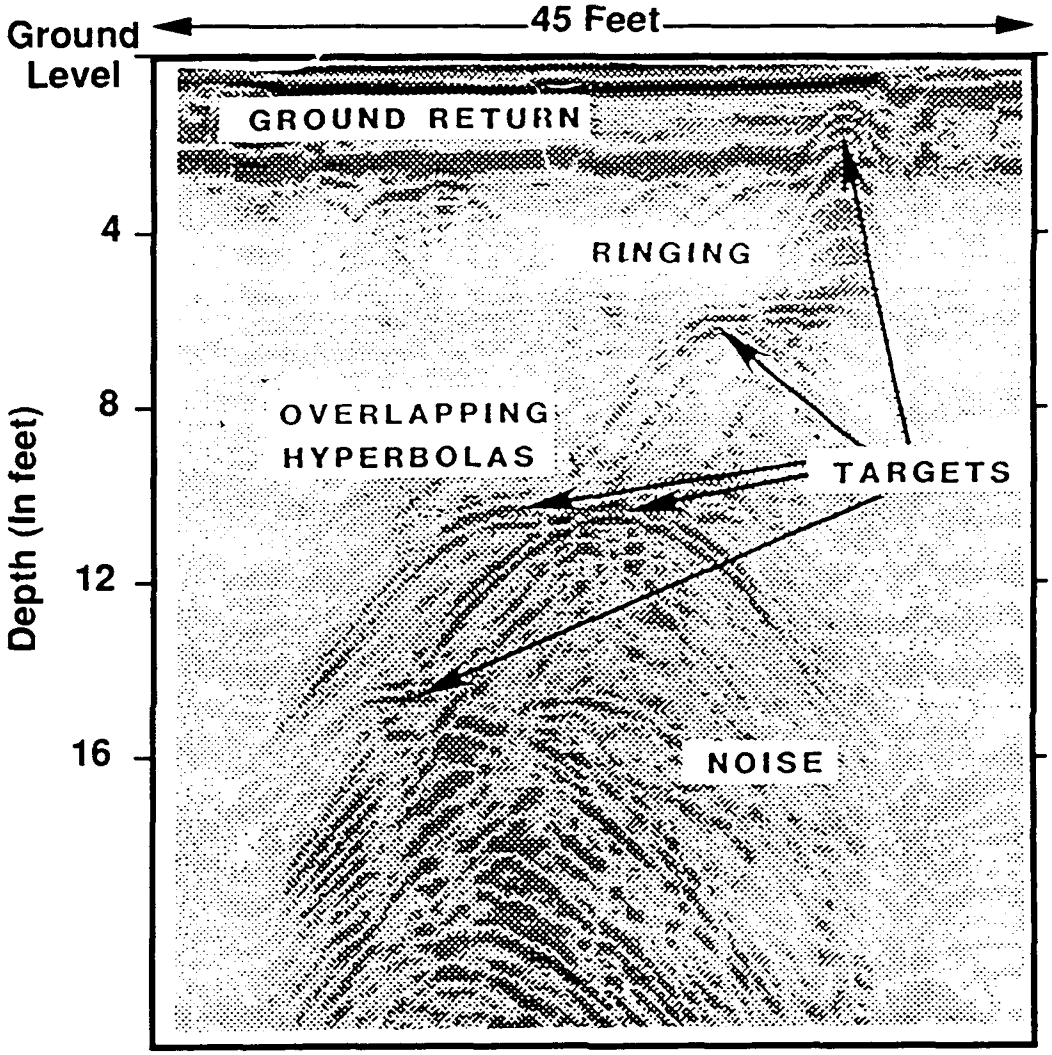
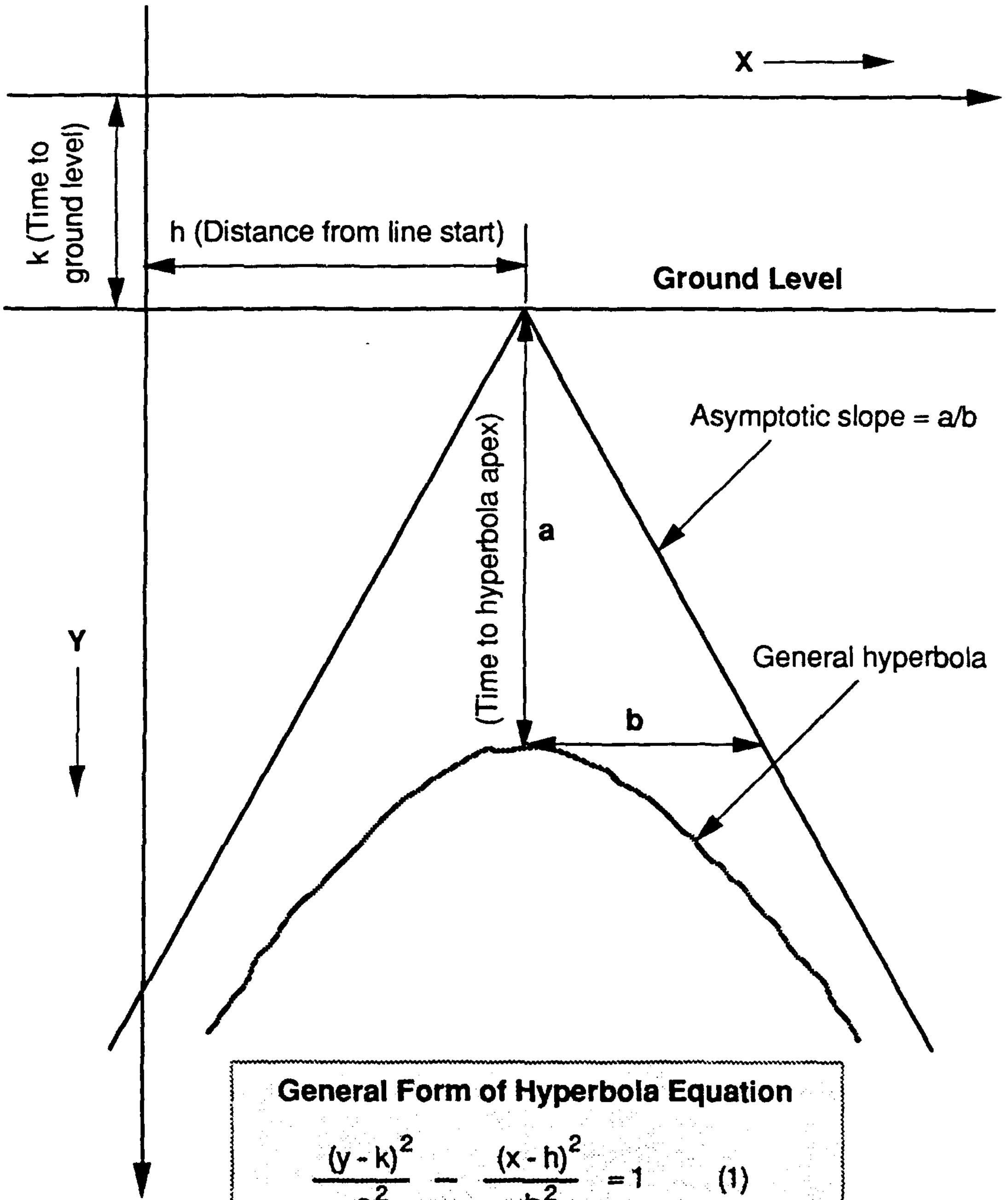


Figure A - 1.

Digitized GPR Data Over Sand Filled Test Pit



General Form of Hyperbola Equation

$$\frac{(y-k)^2}{a^2} - \frac{(x-h)^2}{b^2} = 1 \qquad (1)$$

Figure A-2.

General Form and Equation for Hyperbola

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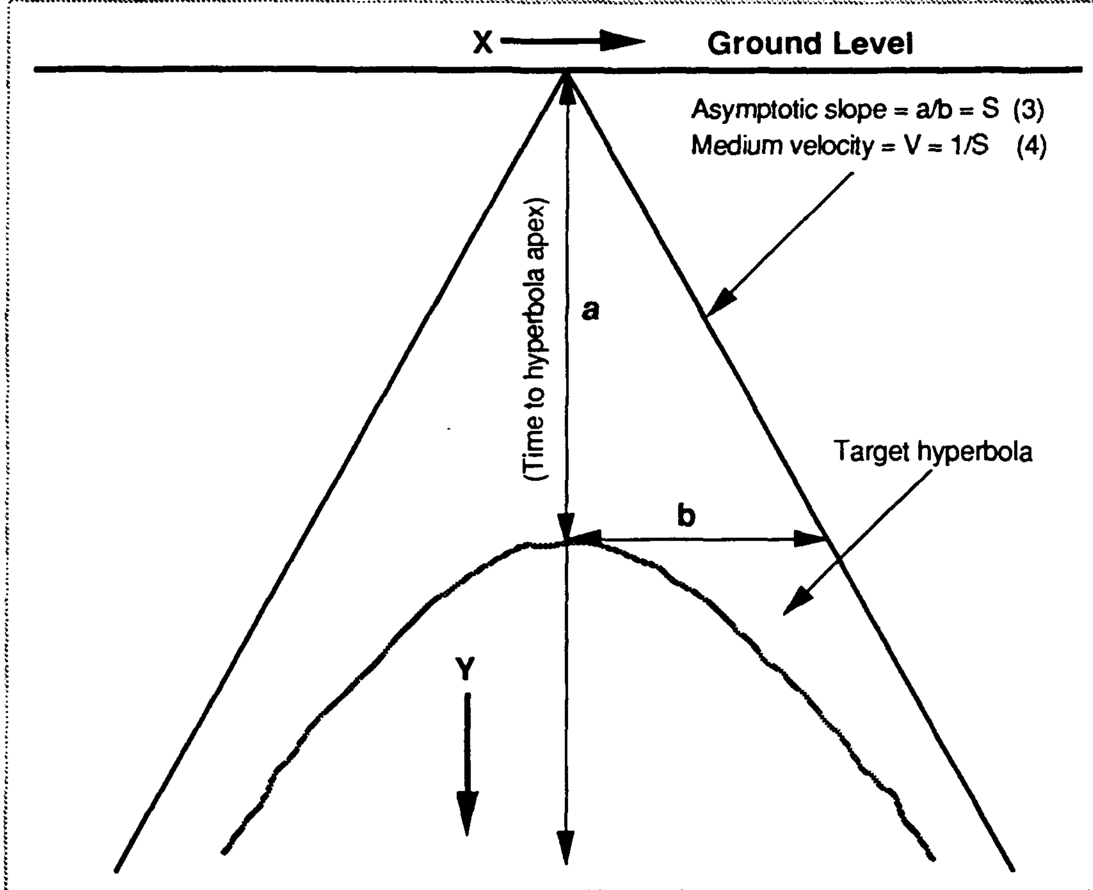

The coordinate system is centered over a target hyperbola at the ground level, hence k = h = 0. The general form (eq. 1) becomes:

$$\frac{y^2}{a^2} - \frac{x^2}{b^2} = 1 \qquad (2)$$

using eqs. 2 and 3, eq. 4 can be rewritten as:

$$y = \sqrt{a^2 + \frac{x^2}{V^2}} \qquad (5)$$

The only parameters needed to define the hyperbola are **a** and **V** (or **S**). Using the interactive Analysis module, a hyperbola is drawn (eq. 5) on the screen (its apex at a depth **a** and overlaid on a target hyperbola. The shape of the overlaid hyperbola is adjusted by trying various values of **V** until a matching hyperbola is generated. In this manner the medium velocity is easily obtained.

Figure A-3.

Determining Medium (Earth) Velocity from Specific Form and Equation for Target Hyperbola

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The hyperbola described by Equation 5 involves only two parameters, a, the time from the ground surface to the hyperbola apex, and V, the medium velocity. In the Interactive Velocity Analysis module a mouse is used to locate the apex of a target hyperbola (a is determined) and then to adjust the shape of an overlaid hyperbola so that it matches the target hyperbola. The adjustment is simply a trial and error changing of the "narrowness" or "wideness" of the hyperbola accomplished by changing the asymptotic slope (S) or velocity of the overlaid curve. When a satisfactory overlaid fit is achieved, the velocity value used to generate the appropriate overlaid curve is the desired electromagnetic wave propagation velocity.

APPENDIX B
KIRCHOFF MIGRATION THEORY

Kirchoff migration images reflectors such that their true locations in the subsurface can be determined. According to the reflection model, the total reflected wave is a sum of reflections from each point on each reflector. Therefore, proper migration of data from any point reflector allows for proper migration of any structure. This section describes the mathematical overview of the Kirchoff migration method used. The concepts presented here can be found in several works, particularly, "Migration of Seismic Data", edited by Gerald H.F. Gardner, Society of Exploration Geophysicists, Geophysics reprint series No. 4.

Consider radar data arising from a point reflector at location x,z. The result is a radar pulse along a travel time or characteristic hyperbolic curve t_D (X,x,z). The lowercase parameters indicate position in the earth and the uppercase parameters indicate position along the hyperbolic curve. The construction of the curve t_D is shown in Figure B-1. The travel time curve can be calculated if the geometry and electromagnetic velocity, V, are known. The travel time is:

$$t_D\ (X,x,z) = 2\ [(t_0/2)^2 + ((x-X)/V)^2]^{1/2} \qquad \text{B-1}$$

This is the characteristic hyperbolic signature seen in unmigrated radar data generated from point reflectors in the earth.

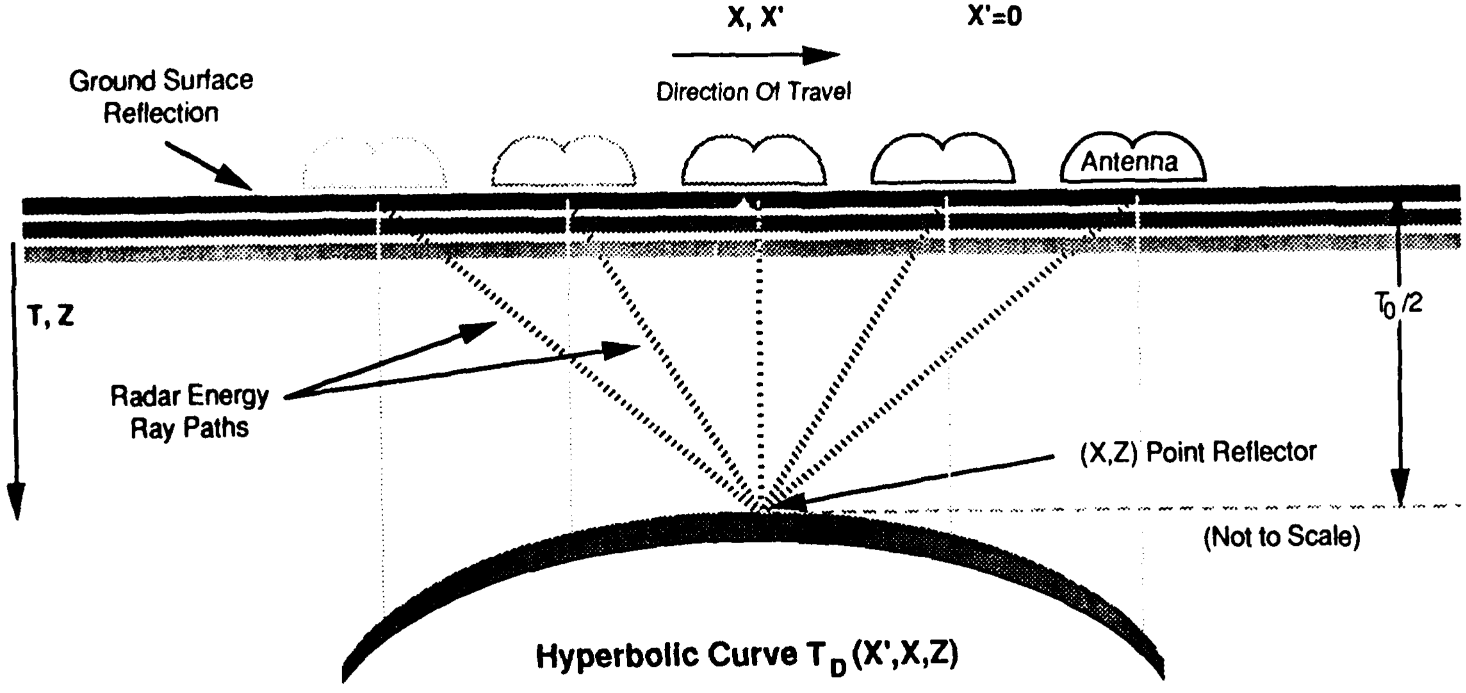
To create an image of the reflection point x, z, all of the data samples along the hyperbolic curve are summed, so that all of the data add up in phase, i.e.,

$$M(x,z) = \int dX\ D(X,t=t_D(X,x,z)) \qquad \text{B-2}$$

where M(x,z) is the migrated data at point x,z, and D(X,t) is the data at distance X and time t. The contributions from other reflection points will not add up in phase, and will therefore make only a minor contribution to M(x,z). By performing this operation for all x and z, a complete image of the reflectors is obtained.

Although the coherent summation of eq. A-1 will image reflections at their proper positions, modifications to the equation are needed to preserve waveform and amplitude. If the radar pulse is P, and a continuous reflector has a travel time curve, $t_R(x)$, then the observed data will be

$$D(x,t) = P(t - t_R(x)) \qquad \text{B-3}$$



Kirchoff Migration Integral, $M(X, T_0) \alpha \int dx\, T\ (X',X,T\ ) \cdot C(X',T\ ,\omega)_0$
C is a summary correction factor for distortions in both phase and amplitude.

Figure B-1.

Hyperbolic Curve from a Point Reflector

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The migration of the reflector using equation A-2 yields:

$$M(x,t_0) = \int dX\ D(X,t_D(x,X,t_0)) = \int dX\ P(t_D\ (X,x,t_0)-t_R(X)) \qquad \text{B-4}$$

Geometrically, the output of migration is dominated by the point at which the data is tangent to the hyperbolic curve, because this is where the data add coherently in the Kirchoff integral. A mathematical examination of this point is as follows. Writing the input pulse as a Fourier transform

$$P(T) = \int d\omega\ \exp\{i\omega(t_D(X,x,t_0)-t_R(X))\}\ P(\omega) \qquad \text{B-5}$$

The principle of stationary phase (Jackson, 1975) indicates that the integral is dominated by a small region around the distance X_0 at the point of tangency,

$$[\partial/\partial X(t_D - t_R)]X=X_0 = 0 \qquad \text{B-6}$$

Since the integral is dominated by $X = X_0$, a Taylor expansion of $t_D - t_R$ with respect to X about X_0 can be performed and equation A-4 can now be written as

$$M(x,t_0) \approx \int d\omega\ \exp\{i\omega(t_D-t_R)_0\}P(\omega)\ \int dX\ \exp[i\omega C(X-X_0)^2/2] \qquad \text{B-7}$$

where

$$C = [\partial^2/\partial X^2\ (t_D-t_R)]_0$$

The X integral can be performed analytically and the result substituted into equation A-7 to yield

$$M(x,t_0) = (2\pi)^{1/2}[(i\omega)^{-1/2}*P]\{t_D(X,x,t_0)-t_R(X_0)\}\ [\partial^2/\partial X^2(t_D-t_R)]_0-1/2 \qquad \text{B-8}$$

As a result of the summation process, the wavelet has been distorted, a) in phase by convolution with a filter $(i\omega)^{-1/2}$, b) in amplitude by a factor of $(2\pi)^{1/2}\ [\partial^2\partial x^2(t_D-t_R)]_{0-1/2}$, and c) through the elongation of the pulse itself by a factor of $[\partial Td/\partial\ t_0]_{0-1}$.

The phase distortion can be compensated for by applying a filter $(i\omega)^{1/2}$ to the input data. It is implemented by transforming each input trace to frequency, multiplying by $(i\omega)^{1/2}$, then inverting the Fourier transform. The amplitude distortion can be corrected by setting

$$\partial^2/\partial X^2(t_D-t_R) = \partial^2 t_D/\partial X^2$$

and including the factor $(\partial^2 t_D/\partial X^2)^{1/2}$ in the Kirchoff integral.

The elongation of the radar pulse cannot be eliminated but can be controlled. It is due to the fact that migration treats a reflector with a uniform thickness equal to the time duration of the radar pulse. From eq. 6 it is seen that a pulse of duration Δt yields a vertical travel time thickness of $\Delta t\ (\partial t_D/\partial t_0)^{-1}$. Since $\partial t_D/\partial t_0$ is not a constant, the travel time elongation of the pulse that occurs increases with lateral distance from the center of the hyperbolic curve. If the factor, $(\partial t_D/\partial t_0)^{-1}$, is too great, then the resulting migration summation is distorted. A limit can be set on the allowable increase by limiting distance along the hyperbola on which migration is performed.

Thus the final form for Kirchoff integral migration is

$$M(x,t_0) = (2\pi)^{-1/2} \int dX \frac{[(i\omega^{1/2} * D](X,t_D(X,x,t_0))}{[\partial^2 t_D/\partial X^2]^{1/2}} \qquad \text{B-9}$$

For discretely sampled data, this becomes

$$M(x,t_0) = (2\pi)^{-1/2} 2(\Delta x) \sum_X \frac{[(i\omega)^{1/2} * D](X,t_D(X,x,t_0))}{[\partial^2 t_D/\partial X^2]^{1/2}} \qquad \text{B-10}$$

where Δ x is the distance between acquired traces.

APPENDIX C

Recommended Upgrades

The following upgrades are recommended to raise system performance, increase reliability, and improve overall ruggedness.

RADAR Tow Vehicle

- Add engine compartment heat vent
- Incorporate an optical disk storage rack
- Upgrade the stock air conditioner to keep equipment in operating range
- Upgrade the battery chargers to two stage chargers and incorporate a volt meter to compliment the current meter for monitoring state of charge
- Upgrade the OCDC CPU to a 386 or 486 machine with higher operating temperature specification
- Rework the RADSIB board to allow multiple direct memory accesses
- Upgrade OCDC software as follows:

    - Rewrite in higher level (C) language
    - Incorporate DMA write to optical disk
    - Add an exit option to the playback routine
    - Implement real time display of all GPR, navigation, tick wheel, and status data
    - Expand the GPR setup routine to allow range gain functions for each antenna
    - Add a RADAR Controller diagnostic check and re-enable the navigation check
    - Incorporate "OPTDIR" and "OPTCHK" utilities
    - Upgrade the Optical Disk capacity routine to properly handle single and double sided disks
    - Store the application software in EPROM

- Optimize RADAR Controller (RC) low pass filters
- Upgrade RC front panel LEDs
- Improve navigation accuracy with new land based applications software and add a DC power supply to the Racal CMU

- Upgrade Track Guidance front panel LEDs and back light LCD displays
- Power the Track Guidance Unit from the vehicle 12 VDC supply

RADAR Tow Platform

- Redesign antenna support scheme to allow antennas to pitch in rough, off-road environments
- Extend hitch for full operation of the tow vehicle tailgate
- Rebuild and spare all cable assemblies

Remote Navigation Stations

- Specify and procure telescoping tripods
- Fabricate and spare new cables
- Upgrade power/signal connector on all T/Rs

RADAR Command Center

- Redesign access ramps
- Upgrade computer CPU to one or more CPU-32 boards for faster post processing.
- Upgrade software to:

  - Port application software to upgraded CPU(s)
  - Vertically normalize GPR data
  - Optimize algorithms for site dependant variables and faster execution
  - Upgrade setup routine to handle survey data on multiple optical disks
  - Add hard disk free block check to preprocessing task

RADAR Utility Assessment

- Single channel GPR site calibration
- DC resistivity
- EM conductivity
- USGS expert system evaluation model

Multi-frequency GPR

Multi-frequency GPR antenna options should be considered as part of the next generation RADAR.

APPENDIX D

Next Generation System

The next generation of RADAR will be designed taking into consideration the knowledge and experience gained with the developmental prototype system. Major advances in the fields of sensor technology, electrical engineering, terrestrial navigation, and information processing promise increased detection probabilities, lower false alarm rates, real time processing, and autonomous operation.

The next generation system will incorporate engineering changes which will significantly improve the system robustness, performance speed, and accuracy and range of application. Much valuable information now exists which will be utilized to provide rugged, fieldable equipment, which will be constructed and documented consistent with Mil-Standard 100 Level 2 documentation.

System hardware will be selected and designed to meet specified terrain and climatic conditions. A prime mover tow vehicle must withstand the typical off-road, military service requirements. Typical examples are the High Mobility Multi-Wheel Vehicle (HMMWV) or the Army standard issue (CUCV-D) truck.

On-line diagnostics will be provided through the implementation of real time operator interactive display of radar, navigation, tick wheel, and status data. An upgraded optical disk storage device using direct memory access will free up CPU time for additional upgrades including control and operation with multiple frequency GPR antenna arrays. The optical disk will also store survey setup records thereby minimizing setup time and associated operator errors and inaccuracies. The RADAR applications programs will be stored on ROMs.

The tow platform will incorporate multiple frequency GPR antennas to optimize data in a single survey. Higher (900 MHz) frequency antennas will enhance near surface resolution while lower (120 MHz) frequency antennas will enhance survey depth capabilities. Existing 300 MHz GPR antennas will maintain current capabilities. All antennas will be attached using a design which will maximize sensor to ground coupling in off-road environments.

The command center will be a climate controlled shelter which is capable of providing an environment which is "computer" friendly. This applies to temperature, humidity and cleanliness, as well as to the quality of electrical power and equipment shock mounting. A customized over-the-road tractor trailer equipped with a suitable air lock is required to provide the basis of such a command center, and to be able to deploy it in a rapid fashion to widely varying locations.

The computer system software (operating system and application code) will be robust and user friendly for operation by a wide range of personnel operating skills. To accomplish this, a widely accepted, supported and universal operating system will be incorporated and high level programming languages will be utilized for non-process time critical routines, thereby allowing simple and easily used software. The computer CPU will be upgraded to a faster processor with on board memory management. This improvement will reduce survey data process time.

A data library will be provided based on actual survey data gathered in varying geological conditions using the present equipment. Following full evaluation of this data, processing algorithms will be optimized and categorized by geological condition(s). In addition, algorithms may be implemented on a set

of multiple parallel digital signal processors allowing additional improvements in processing speeds.

Automatic signal processing algorithms will be expanded to identify a wider range of targets to include ordnance or target clusters, underground voids produced by exploded ordnance and detection of smaller/shallow targets. By providing various antenna configurations and frequencies a wide range of survey requirements may be met. Optimization for geological conditions, survey depth, and target types could then occur.

Power interruption protection will be provided to the computer system. On-line help menus and sub-menus will be provided to increase user friendliness. Directory listing capability will be accessible from within the "RADAR" applications processing program. A maximum file check routine will automatically alert the operator to the available storage capacity so that data transfer decisions can be made analytically and before the fact.

The navigation system will incorporate land based applications software which is now becoming available. A global positioning survey system which could be updated locally via satellite would provide three-dimensional data for increased remote navigation station location accuracy.

Finally an integrated handheld unit would be incorporated and tied into the navigation system in order to complement wide area surveys in areas not covered due to rough or unnavigable terrain.

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